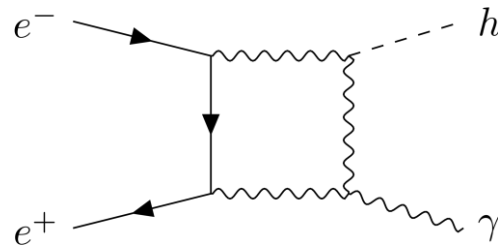


PROBING TYPE-II SEESAW THROUGH RARE HIGGS PROCESSES

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INTRODUCTION

Standard model [Glashow, 1961, Weinberg, 1967, Salam, 1968]

- Mass terms for $Z, W^\pm$ prohibited by gauge invariance
- 1964: Brout-Englert-Higgs (BEH) mechanism
[Higgs, 1964, Brout and Englert, 1964, Guralnik et al., 1964]
→ massive $Z, W^\pm$ and charged fermions
→ **Neutrinos remain massless.**

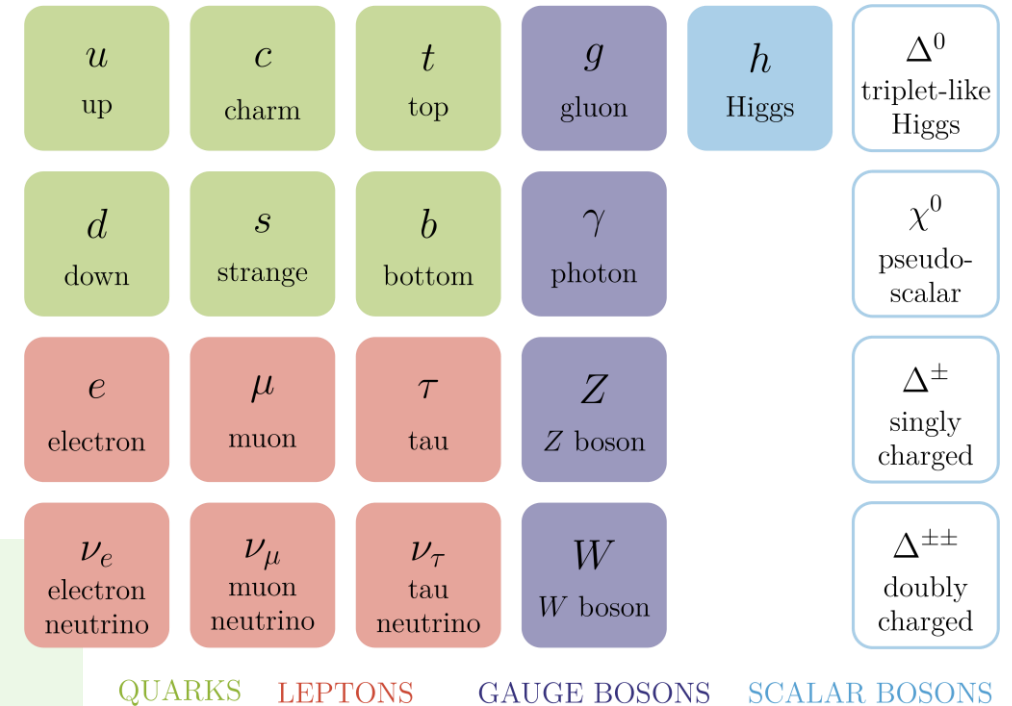
beyond the Standard model

1998: Neutrino oscillations → massive neutrinos

[Fukuda et al., 1998]

- Type-I: heavy right-handed neutrino singlets [Minkowski, 1977]
- **Type-II:** triplet of complex scalars [Magg and Wetterich, 1980, Senjanović and Mohapatra, 1981, Cheng and Li, 1980]
- Type-III: triplet of left-handed fermions [Foot et al., 1989]

Figure 1: Field content of Type-II Seesaw.



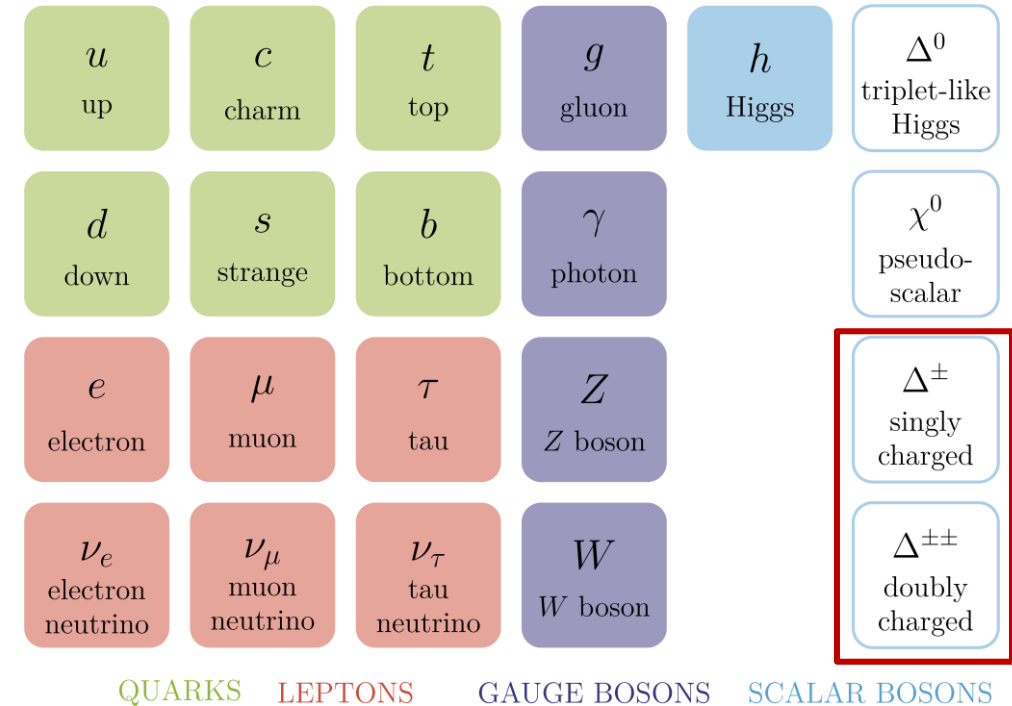
Seesaw mechanism. Neutrino masses inversely proportional to masses of new, BSM particles.

INTRODUCTION

Probing BSM models

- **Direct searches:** observing production and decays of BSM particles
- **Indirect searches:** effects of BSM particles in processes of known SM particles
 - Rare loop-induced processes are particularly sensitive to BSM phenomena.

Figure 1: Field content of Type-II Seesaw.



Type-II Seesaw

- Scalar sector contains charged scalar states, which couple to γ , Z , h

We explored Type-II signatures in

- $h \rightarrow \gamma\gamma$
- $h \rightarrow Z\gamma$
- $e^+e^- \rightarrow h\gamma$

- (predominantly) loop-induced
- LO Type-II contributions from charged scalar loops

The three investigated processes:

$$h \rightarrow \gamma\gamma \quad h \rightarrow Z\gamma$$

LEP and ATLAS measurement

[Aad et al., 2023] [Sirunyan et al., 2021]
[Aad et al., 2020] [Tumasyan et al., 2023]

$$e^+e^- \rightarrow h\gamma$$

CERN's future electron-positron
colliders:
FCC-ee, LCF, CLIC

My thesis includes:

- Derivation of the analytic amplitudes
- Constraints from $h \rightarrow \gamma\gamma$, $h \rightarrow Z\gamma$
- Analysis of $e^+e^- \rightarrow h\gamma$ as a future probe for Type-II

analytic formulae for
the associated Higgs
production in Type-II

Overview of existing literature:

- $h \rightarrow \gamma\gamma$ decay: first SM analytics papers: [Nanopoulos et al., 1976, Voloshin et al., 1979]
- $h \rightarrow Z\gamma$ decay: [Cahn et al., 1979]
- $e^+e^- \rightarrow h\gamma$ scattering: [Bergstrom and Hulth, 1985, Romão et al., 1986]

modern reviews:

- [Djouadi, 2008, Marciano et al., 2012]
- [Djouadi, 2008]
- [Djouadi, 2008]

BSM analytics: [Djouadi, 2008, Chen et al., 2013]

Type-II phenomenology:

- [Arhrib et al., 2019, Nemevšek et al., 2011]

PART I:

Theoretical framework

Explaining neutrino masses with Type-II Seesaw

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

The Δ triplet

- Introduce a triplet of complex scalars in the adjoint representation of SU(2)

$$\Delta = \sum_{a=1}^3 \Delta_a T_f^a$$

$$T_f^a = \frac{\tau^a}{\sqrt{2}}$$

generators in
the fund. rep.

$$\Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^3 & \Delta^1 - i\Delta^2 \\ \Delta^1 + i\Delta^2 & -\Delta^3 \end{pmatrix}$$

with hypercharge: $Y_\Delta = 1$

- Transformation under SU(2): $\Delta \rightarrow \Delta' = U \Delta U^{-1}$ $U = \exp(i\varepsilon_a T_f^a) \in \text{SU}(2)$

$$\Delta' \simeq (\mathbb{1} + i\alpha_i T_f^i) \Delta (\mathbb{1} - i\alpha_i T_f^i) \simeq \Delta + i\alpha [T_f^i, \Delta]$$

$$\Delta' \simeq \Delta + i\alpha_i T_{\text{adj}}^i \Delta \quad T_{\text{adj}}^i(\Delta) = [T_f^i, \Delta]$$

Pauli matrices

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$(T_{\text{adj}}^a)_{bc} = -i\varepsilon_{abc}$$

generators in
the adj. rep.

- Using the definition of electromagnetic charge $Q = T_3 + Y$

we find the charges of the Δ fields

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$$

- singly and doubly charged components of the triplet
- neutral component

$$\lambda_{h\Delta 1} + \lambda_{h\Delta 2} \equiv \lambda_{h\Delta}$$

$$\lambda_{\Delta 1} + \lambda_{\Delta 2} \equiv \lambda_{\Delta}$$

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

Scalar potential and symmetry breaking

- Constructed from all renormalizable gauge-invariant terms involving Higgs doublet and Δ triplet

SM scalar potential

$$V_{\Delta} = \left[-\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2 \right] + m_{\Delta}^2 \text{Tr} [\Delta^\dagger \Delta] + \lambda_{\Delta 1} (\text{Tr} [\Delta^\dagger \Delta])^2 + \lambda_{\Delta 2} \text{Tr} [(\Delta^\dagger \Delta)^2] \\ + \lambda_{h\Delta 1} \phi^\dagger \phi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \phi^\dagger \Delta \Delta^\dagger \phi + \mu_{h\Delta} (\phi^T (i\tau_2) \Delta^\dagger \phi + \text{h.c.})$$

- Electroweak gauge group spontaneously broken by the vevs of the scalar multiplets

➤ Only neutral components acquire non-zero vevs:

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Delta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{\Delta} & 0 \end{pmatrix}$$

Higgs vev triplet vev

- From Δ kinetic terms upon SSB

- Requiring the potential minimized by the two vevs

2 minimization conditions:

$$\frac{\partial V(\langle \phi \rangle, \langle \Delta \rangle)}{\partial v} = 0$$

$$\frac{\partial V(\langle \phi \rangle, \langle \Delta \rangle)}{\partial v_{\Delta}} = 0$$

$$\mu_h^2 = \lambda_h v^2 - \frac{v_{\Delta}^2}{2v^2} (4m_{\Delta}^2 + \lambda_{h\Delta} v^2) - 2 \frac{v_{\Delta}^4}{v^4} \lambda_{\Delta} v^2, \quad (1)$$

$$\mu_{h\Delta} = \sqrt{2} v_{\Delta} \left(\frac{m_{\Delta}^2}{v^2} + \frac{1}{2} \lambda_{h\Delta} + \lambda_{\Delta} \frac{v_{\Delta}^2}{v^2} \right) \quad (2)$$

Type-II corrections to the electroweak boson masses:

- $\delta m_W^2 = g^2 v_{\Delta}^2,$
- $\delta m_Z^2 = \frac{1}{2} (g^2 + g'^2) v_{\Delta}^2,$
- $\delta m_A^2 = 0.$

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

Constraints on the triplet vev

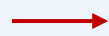
- **ρ parameter:** $\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$
 - SM prediction: $\rho = 1$
 - experimental value: $\rho_{\text{exp}} = 1.00031 \pm 0.00019$
[Navas et al., 2024]

- in Type-II Seesaw: $\rho_{\text{Type-II}} = \frac{(m_{W, \text{SM}}^2 + \delta m_W^2)}{(m_{Z, \text{SM}}^2 + \delta m_Z^2) \cos^2 \theta_W} \approx 1 - 2v_\Delta^2/v^2$

- From the lower 2σ experimental estimate of ρ and the Higgs vev:

$$v \approx 246 \text{ GeV}$$

$$v_\Delta \lesssim 1.5 \text{ GeV}$$



$$v_\Delta \ll v$$

upper bound on
the triplet vev

➤ triplet vev negligible
w. r. t. Higgs vev

- the amplitudes derived in the small- v_Δ limit: $v_\Delta \rightarrow 0$

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

Neutrino masses in Type-II Seesaw

- Δ triplet allows the construction of additional gauge-invariant Majorana-type Yukawa terms:

$$\mathcal{L}_{Y\Delta} = -Y_{\Delta}^{ij} \overline{L}_i^c (i\tau_2) \Delta L_j + \text{h.c.}$$

Y_{Δ} : **Yukawa matrix**
 i, j : generation indices

Majorana neutrinos: $\nu^c(x) = \nu(x)$

charge conjugation:

$$\psi^c = C\bar{\psi}^T, \quad C \equiv i\gamma^2\gamma^0$$

SSB

$$\mathcal{L}_{Y\Delta} = -Y_{\Delta}^{ij} \overline{L}_i^c (i\tau_2) \langle \Delta \rangle L_j + \text{h.c.} = -Y_{\Delta}^{ij} \frac{v_{\Delta}}{\sqrt{2}} \overline{\nu}_{Li}^c \nu_{Lj} + \text{h.c.}$$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} M_{ij} \overline{\nu}_{Li}^c \nu_{Lj}$$



$$M_{\nu} = \sqrt{2} Y_{\Delta} v_{\Delta}$$

neutrino mass matrix

- Type-II Seesaw includes mass terms for the neutrinos.
- Neutrino masses proportional to v_{Δ}

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

Scalar ‘zoo’ in Type-II Seesaw

- 2 + 3 complex scalars = **10** scalar degrees of freedom
- Perturbing the fields around the vevs:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}w^+ \\ v + h^0 + iz \end{pmatrix}, \quad \Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta^+ & \sqrt{2}\delta^{++} \\ v_\Delta + \delta + i\chi & -\delta^+ \end{pmatrix}$$

- Introduced real (h, z, δ, χ) and complex ($w^+, \delta^+, \delta^{++}$) scalar fields
- Arranged based on their quantum numbers

◇ neutral CP-even: $h^0, \delta \rightarrow h, \Delta^0$

◇ singly charged: $w^\pm, \delta^\pm \rightarrow G^\pm, \Delta^\pm$

◇ neutral CP-odd: $z, \chi \rightarrow G^0, \chi^0$

◇ doubly charged: $\delta^{\pm\pm} \equiv \Delta^{\pm\pm}$

➤ They mix to form **mass eigenstates**.

EXTENDING THE STANDARD MODEL TO TYPE-II SEESAW

Scalar ‘zoo’ in Type-II Seesaw

- To find the mass eigenstates, diagonalize 2x2 real symmetric mass matrices
- For $v_\Delta \rightarrow 0$, the mixing is small; mass eigenstates aligned with the multiplet states

Scalar masses in the small- v_Δ limit:

TRIPLET-LIKE STATES	SM-LIKE STATES
$\left. \begin{aligned} m_{\Delta^{\pm\pm}}^2 &\simeq m_\Delta^2 + \frac{1}{2}\lambda_{h\Delta 1}v^2, \\ m_{\Delta^\pm}^2 &\simeq m_{\Delta^{\pm\pm}}^2 + \frac{1}{4}\lambda_{h\Delta 2}v^2, \end{aligned} \right\} \begin{array}{l} \Delta^{\pm\pm}, \Delta^\pm \\ \text{singly and} \\ \text{doubly charged} \\ \text{scalars} \end{array}$	$m_h^2 \simeq 2\lambda_h v^2, \quad \text{SM-like Higgs } h$
$m_{\chi^0}^2 \simeq m_{\Delta^0}^2 \simeq m_{\Delta^{\pm\pm}}^2 + \frac{1}{2}\lambda_{h\Delta 2}v^2,$ massive pseudoscalar χ^0 triplet-like Higgs Δ^0	$\left. \begin{aligned} m_{G^\pm}^2 &= 0, \\ m_{G^0}^2 &= 0. \end{aligned} \right\} \begin{array}{l} \text{would-be} \\ \text{Goldstones} \\ G^\pm, G^0 \end{array}$

PART II:

Phenomenology

Exploring loop-induced Higgs processes in Type-II Seesaw

Parameters of Type-II Seesaw

$$V_\Delta = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2 + m_\Delta^2 \text{Tr} [\Delta^\dagger \Delta] + \lambda_{\Delta 1} (\text{Tr} [\Delta^\dagger \Delta])^2 + \lambda_{\Delta 2} \text{Tr} [(\Delta^\dagger \Delta)^2] \\ + \lambda_{h\Delta 1} \phi^\dagger \phi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \phi^\dagger \Delta \Delta^\dagger \phi + \mu_{h\Delta} (\phi^T (i\tau_2) \Delta^\dagger \phi + \text{h.c.})$$

SM parameters

- λ_h, v fixed to SM values
- μ_h from min. cond. (1)

Label	Parameter
μ_h	Higgs mass parameter
λ_h	Higgs quartic coupling
m_Δ	triplet mass parameter
$\lambda_{\Delta 1}, \lambda_{\Delta 2}$	triplet quartic couplings
$\lambda_{h\Delta 1}, \lambda_{h\Delta 2}$	Higgs-triplet bi-quadratic couplings
$\mu_{h\Delta}$	Higgs-triplet trilinear coupling
v	Higgs vev
v_Δ	triplet vev

10 parameters of Type-II potential in the broken phase;
 → **8 independent**
 → 2 min. cond.

$$\mu_h^2 = \lambda_h v^2 - \frac{v_\Delta^2}{2v^2} (4m_\Delta^2 + \lambda_{h\Delta} v^2) - 2 \frac{v_\Delta^4}{v^4} \lambda_\Delta v^2, \quad (1)$$

$$\mu_{h\Delta} = \sqrt{2} v_\Delta \left(\frac{m_\Delta^2}{v^2} + \frac{1}{2} \lambda_{h\Delta} + \lambda_\Delta \frac{v_\Delta^2}{v^2} \right) \quad (2)$$

Parameters of Type-II Seesaw

$$V_\Delta = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2 + m_\Delta^2 \text{Tr} [\Delta^\dagger \Delta] + \lambda_{\Delta 1} (\text{Tr} [\Delta^\dagger \Delta])^2 + \lambda_{\Delta 2} \text{Tr} [(\Delta^\dagger \Delta)^2] \\ + \lambda_{h\Delta 1} \phi^\dagger \phi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \phi^\dagger \Delta \Delta^\dagger \phi + \mu_{h\Delta} (\phi^T (i\tau_2) \Delta^\dagger \phi + \text{h.c.})$$

SM parameters

- λ_h, v fixed to SM values
- μ_h from min. cond. (1)

Type-II parameters

- $\mu_{h\Delta}$ from min. cond. (2)

Label	Parameter
μ_h	Higgs mass parameter
λ_h	Higgs quartic coupling
m_Δ	triplet mass parameter
$\lambda_{\Delta 1}, \lambda_{\Delta 2}$	triplet quartic couplings
$\lambda_{h\Delta 1}, \lambda_{h\Delta 2}$	Higgs-triplet bi-quadratic couplings
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$$\mu_{h\Delta} = \sqrt{2} v_\Delta \left(\frac{m_\Delta^2}{v^2} + \frac{1}{2} \lambda_{h\Delta} + \lambda_\Delta \frac{v_\Delta^2}{v^2} \right) \quad (2)$$

The calculation of amplitudes

- Type-II parameter space explored through: $h \rightarrow \gamma\gamma$, $h \rightarrow Z\gamma$, $e^+e^- \rightarrow h\gamma$
- Dominant contributions to the amplitudes at 1-loop

Treatment of Type-II corrections to the amplitudes:

In full generality, corrections are two-fold:

$$\mathcal{M}_{\text{Type-II}} = \mathcal{M}_{\text{SM}}|_{\Delta} + \sum_{\Delta} \mathcal{M}_{\Delta}, \quad \Delta = \{\Delta^{\pm}, \Delta^{\pm\pm}\}$$

SM amplitude modified to
account for the mixing of
scalars

Type-II loops
(charged scalars as
loop states)

- $v_{\Delta} \ll v$: mixing negligible

$$\mathcal{M}_{\text{SM}}|_{\Delta} \simeq \mathcal{M}_{\text{SM}}$$

- Leading-order Type-II corrections enter through charged scalar loops.

- These rare Higgs processes probe couplings of charged scalars to SM-like Higgs, and their masses.

Parameters of Type-II Seesaw

$$V_\Delta = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2 + m_\Delta^2 \text{Tr} [\Delta^\dagger \Delta] + \lambda_{\Delta 1} (\text{Tr} [\Delta^\dagger \Delta])^2 + \lambda_{\Delta 2} \text{Tr} [(\Delta^\dagger \Delta)^2] \\ + \lambda_{h\Delta 1} \phi^\dagger \phi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \phi^\dagger \Delta \Delta^\dagger \phi + \mu_{h\Delta} (\phi^T (i\tau_2) \Delta^\dagger \phi + \text{h.c.})$$

- In the small- v_Δ limit, amplitudes for the 3 processes depend on

Higgs-triplet couplings

$$C_{h\Delta^{\pm\pm}\Delta^{\pm\pm}} \simeq \lambda_{h\Delta 1}.$$

$$C_{h\Delta^\pm\Delta^\pm} \simeq \lambda_{h\Delta 1} + \frac{1}{2}\lambda_{h\Delta 2},$$

Charged scalar masses

$$m_{\Delta^{\pm\pm}}^2 \simeq m_\Delta^2 + \frac{1}{2}\lambda_{h\Delta 1}v^2$$

$$m_{\Delta^\pm}^2 \simeq m_{\Delta^{\pm\pm}}^2 + \frac{1}{4}\lambda_{h\Delta 2}v^2$$

- In terms of parameters of Type-II potential

$$\diamond \lambda_{h\Delta 1}$$

$$\diamond m_\Delta \text{ traded for } m_{\Delta^{\pm\pm}}$$

$$\diamond \lambda_{h\Delta 2} \text{ traded for } m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}$$

Label	Parameter
μ_h	Higgs mass parameter
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**Type-II
parameters**

10 parameters of Type-II potential
in the broken phase;
→ **8 independent**
→ 2 min. cond.

The calculation of amplitudes

Parameter space which we explore through the 3 processes is 3-dim.

$$m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}, \quad m_{\Delta^{\pm\pm}}, \quad \lambda_{h\Delta 1}.$$

mass splitting **mass of the doubly charged** **bi-quadratic coupling**

Mass splitting related to coupling $\lambda_{h\Delta 2}$

$$m_{\Delta^\pm}^2 - m_{\Delta^{\pm\pm}}^2 = \frac{1}{4}\lambda_{h\Delta 2}v^2$$

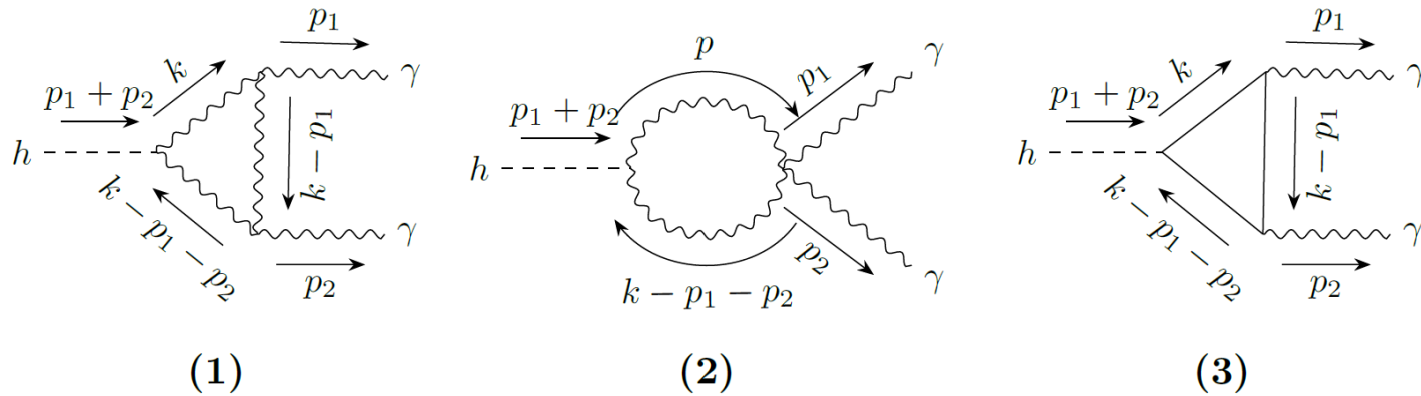
Methods:

- Loop integrals evaluated in Mathematica with Package-X [Patel, 2017]
 - Dimensional regularization
 - Passarino-Veltman reduction [Passarino and Veltman, 1979]
- $h \rightarrow \gamma\gamma$ derived in unitary gauge
- $h \rightarrow Z\gamma, e^+e^- \rightarrow h\gamma$ derived in Feynman-'t Hooft gauge
- Contributing SM diagram topologies cross-checked in FeynArts [Hahn, 2001]
- Numerical evaluation of PV functions in $e^+e^- \rightarrow h\gamma$ amplitude using Python wrapper lt2py [Kriewald, 2026]

Computing $h \rightarrow \gamma\gamma$ decay width

Computing $h \rightarrow \gamma\gamma$ decay width (unitary gauge)

Figure 3: SM diagrams contributing to $h \rightarrow \gamma\gamma$ in unitary gauge.



- W boson loops
- fermion loop
 - main contribution from t, b quarks

After loop integration:

On-shell conditions:

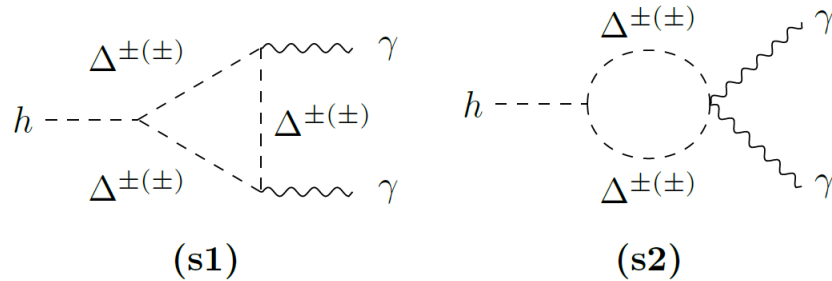
$$(p_1 + p_2)^2 = 2p_1 \cdot p_2 = m_h^2$$

$$p_1^2 = p_2^2 = 0$$

Photon transversality:

$$p_1^\mu \varepsilon_\mu(p_1) = p_2^\nu \varepsilon_\nu(p_2) = 0$$

Figure 4: Type-II diagrams contributing to $h \rightarrow \gamma\gamma$ in unitary gauge.



Computing $h \rightarrow \gamma\gamma$ decay width (unitary gauge)

total SM amplitude

[Ward, 1950]

$$\mathcal{M}_{\text{SM}} = \mathcal{M}_W + \sum_f \mathcal{M}_f = \frac{e^2 g}{(4\pi)^2 m_W} F_{\text{SM}} (p_1 \cdot p_2 g^{\mu\nu} - p_1^\nu p_2^\mu) \varepsilon_\mu(p_1) \varepsilon_\nu(p_2)$$

Ward identities:

$$p_1^\mu \mathcal{M}_\mu = p_2^\nu \mathcal{M}_\nu = 0$$

charged scalar loop amplitude (arbitrary scalar Δ)

$$\mathcal{M}_\Delta = \frac{C_{h\Delta\Delta} v Q_\Delta^2 e^2}{(4\pi)^2 m_\Delta^2} F_\Delta (p_1 \cdot p_2 g^{\mu\nu} - p_1^\nu p_2^\mu) \varepsilon_\mu(p_1) \varepsilon_\nu(p_2)$$

combinations of
PV functions

- total amplitude UV-finite
- satisfies Ward identities

TOTAL TYPE-II DECAY WIDTH ($v_\Delta \ll v$)

$$\Gamma_{h \rightarrow \gamma\gamma}^{\text{Type-II}} = \frac{m_h^3 G_F}{8\sqrt{2}\pi} \left(\frac{\alpha}{4\pi} \right)^2 |F_{\text{Type-II}}|^2, \quad F_{\text{Type-II}} = F_{\text{SM}} + \sum_\Delta \frac{C_{h\Delta\Delta} Q_\Delta^2 v^2}{2m_\Delta^2} F_\Delta, \quad \Delta = \{\Delta^\pm, \Delta^{\pm\pm}\}$$

G_F : Fermi constant

α : fine-structure constant

summed over both charged scalar states

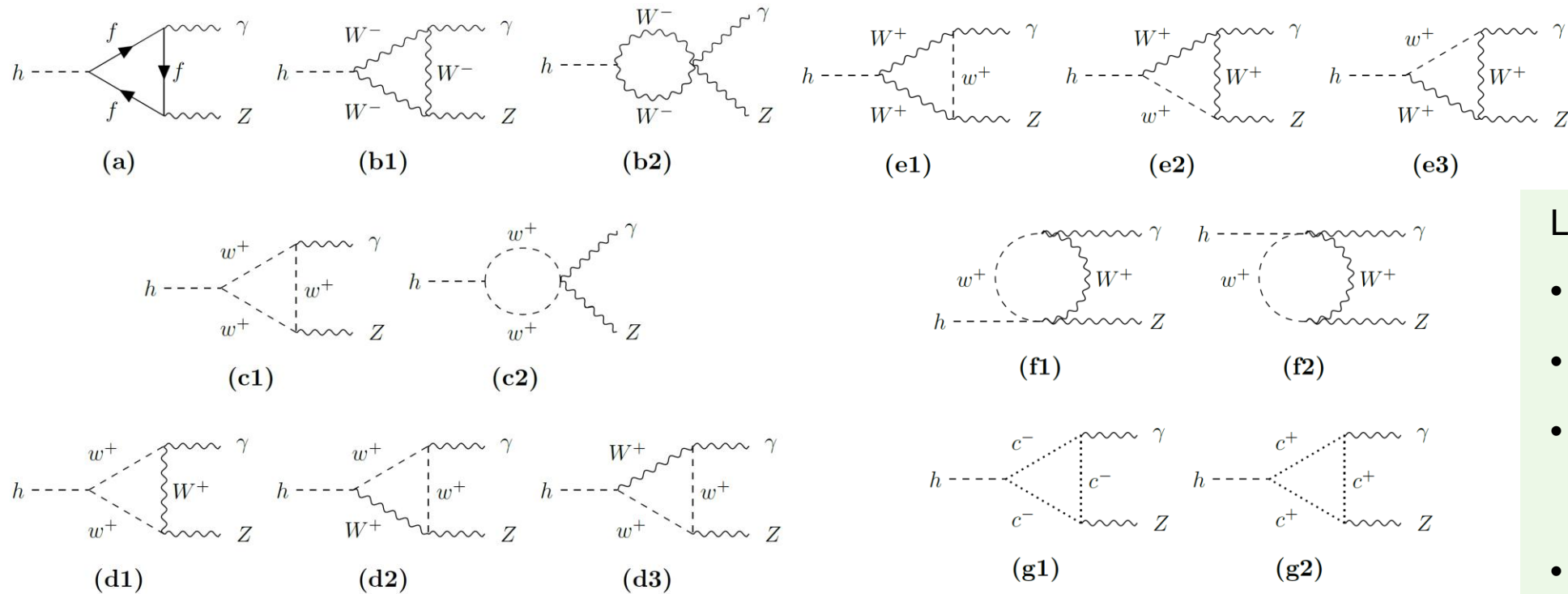
$$C_{h\Delta^\pm\Delta^\pm} \simeq \lambda_{h\Delta 1} + \frac{1}{2}\lambda_{h\Delta 2} \quad Q_{\Delta^\pm} = 1$$

$$C_{h\Delta^{\pm\pm}\Delta^{\pm\pm}} \simeq \lambda_{h\Delta 1} \quad Q_{\Delta^{\pm\pm}} = 2$$

Computing $h \rightarrow Z\gamma$ decay width

Computing $h \rightarrow Z\gamma$ decay width (Feynman-'t Hooft gauge)

One-particle irreducible (1PI) diagrams:



Loop states:

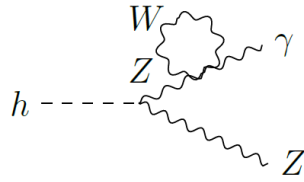
- fermions
- W boson
- charged would-be Goldstones
- ghosts

Figure 5: SM 1PI diagrams contributing to $h \rightarrow Z\gamma$ in Feynman-'t Hooft gauge.

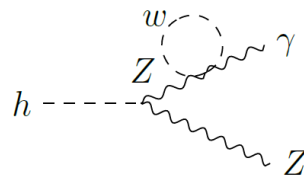
- This set of diagrams is UV-divergent $\mathcal{A}(\text{SM}, 1\text{PI})|_{\text{UV}} = 2eg^2m_Z \frac{g_{\mu\nu}}{\varepsilon}$

Computing $h \rightarrow Z\gamma$ decay width (Feynman-'t Hooft gauge)

Reducible diagrams:

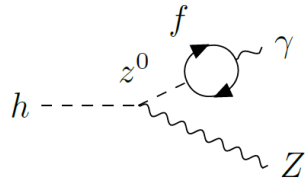


(WFa)

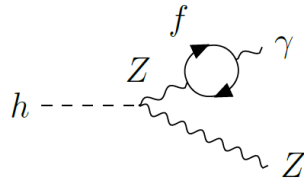


(Wfb)

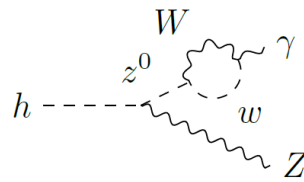
1-loop corrections to Z- γ mixing



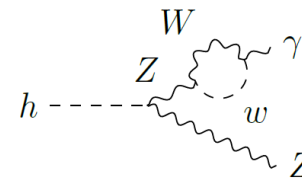
(WFc1)



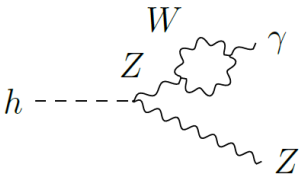
(WFc2)



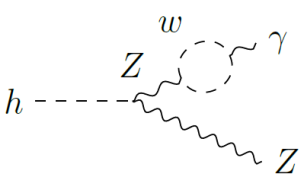
(WFd1)



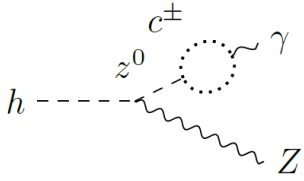
(WFd2)



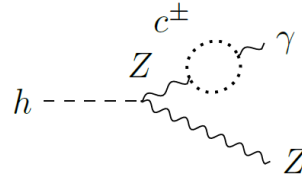
(WFe)



(WFf)



(WFG1)



(WFG2)

Figure 6: SM reducible diagrams contributing to $h \rightarrow Z\gamma$ in Feynman-'t Hooft gauge.

- UV divergence of reducible diagrams

$$\mathcal{A}(\text{SM}, \text{WF})|_{\text{UV}} = -2eg^2m_Z \frac{g_{\mu\nu}}{\varepsilon}$$

cancels against UV div. of 1PI diagrams

$$\mathcal{A}(\text{SM}, 1\text{PI})|_{\text{UV}} = 2eg^2m_Z \frac{g_{\mu\nu}}{\varepsilon}$$

➤ Total amplitude UV-finite

➤ and gauge invariant.

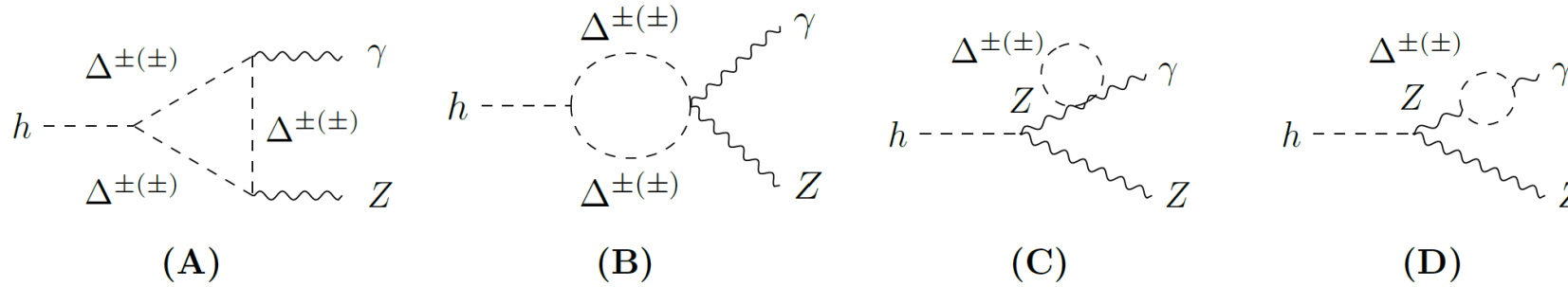
$$p_1^\mu \mathcal{M}_\mu = p_2^\nu \mathcal{M}_\nu = 0$$

(satisfies Ward/Slavnov-Taylor identities)

[Taylor, 1971, Slavnov, 1972]

Computing $h \rightarrow Z\gamma$ decay width (Feynman-'t Hooft gauge)

Figure 7: Type-II diagrams contributing to $h \rightarrow Z\gamma$ in Feynman-'t Hooft gauge.



Type-II couplings

TOTAL TYPE-II DECAY WIDTH:

$$\Gamma_{h \rightarrow Z\gamma}^{\text{Type-II}} = \frac{m_h^3}{32\pi} \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 |F_{h \rightarrow Z\gamma} + A_{\Delta^\pm} F_\Delta(m_{\Delta^\pm}) + A_{\Delta^{\pm\pm}} F_\Delta(m_{\Delta^{\pm\pm}})|^2$$

combinations of PV functions, such as:

$$F_\Delta(m) = m_Z^2 (\Lambda(m_h^2, m, m) - \Lambda(m_Z^2, m, m)) \\ + (m_h^2 - m_Z^2) (1 + 2m^2 C_0(0, m_h^2, m_Z^2, m, m, m))$$

Λ : discontinuity of B_0

Constraining Type-II Seesaw through $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$

Constraining Type-II Seesaw through $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$

Finding the constraints

- Parameters constrained using the experimental measurement of signal strength:

signal strength: $\mu = \frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SM pred}}}$

- For different combinations of parameters, computed χ^2 :

$$\chi^2(m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}, m_{\Delta^{\pm\pm}}, \lambda_{h\Delta 1}) = \left(\frac{\mu_{\text{exp}} - \mu_{\text{pred}}(m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}, m_{\Delta^{\pm\pm}}, \lambda_{h\Delta 1})}{\sigma_\mu} \right)^2$$

- Points in the parameter space for which $\chi^2 > 4$ excluded at $\geq 2\sigma$

Type-II prediction: $\mu_{\text{pred}}(m_{\Delta^\pm} - m_{\Delta^{\pm\pm}}, m_{\Delta^{\pm\pm}}, \lambda_{h\Delta 1}) = \frac{\Gamma_{h \rightarrow \gamma\gamma(Z)}^{\text{Type-II}}}{\Gamma_{h \rightarrow \gamma\gamma(Z)}^{\text{SM}}}$

Measured values: $\mu_{\text{exp}}(h \rightarrow \gamma\gamma) = 1.10 \pm 0.06$

[Navas et al., 2024]

$$\mu_{\text{exp}}(h \rightarrow Z\gamma) = 2.2 \pm 0.7$$

[CMS, 2023]

estimated improved measurement:

$$\mu_{\text{high-lumi}}(h \rightarrow Z\gamma) = 1.0 \pm 0.1$$

[Blas et al., 2025]

Constraining the parameter space

- for positive bi-quadratic coupling, excludes large region with positive mass splitting
- negative $\lambda_{h\Delta 1}$ agrees better with the data, weaker constraints

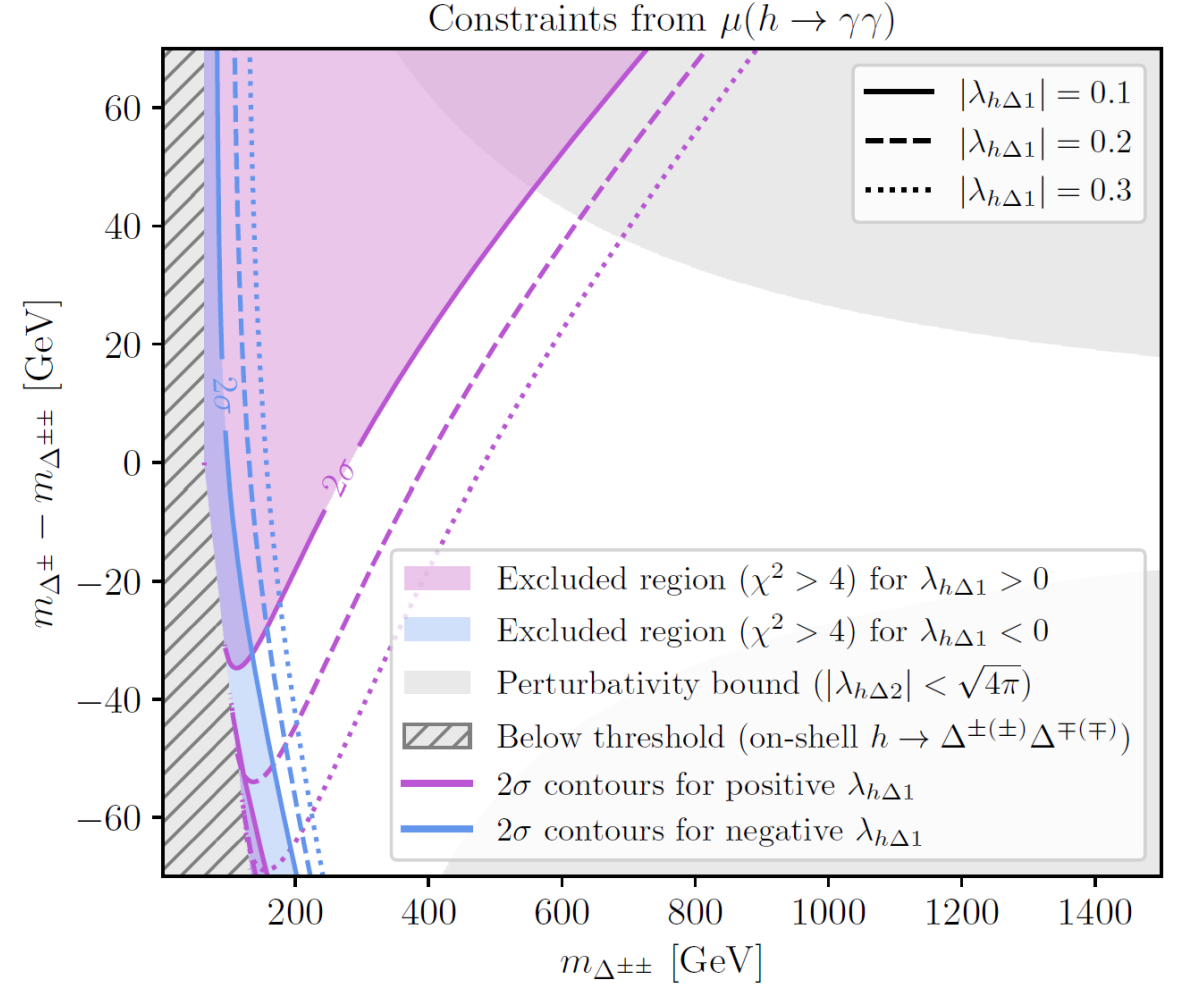


Figure 10: Parameter regions excluded at 2σ for different values of $\lambda_{h\Delta 1}$.

Constraining the parameter space

- Even in the case of improved measurement, constraints from $h \rightarrow Z\gamma$ minuscule
- Related to the suppression of $Z_\mu \Delta^{\pm(\pm)} \Delta^{\mp(\mp)}$ coupling compared to $A_\mu \Delta^{\pm(\pm)} \Delta^{\mp(\mp)}$

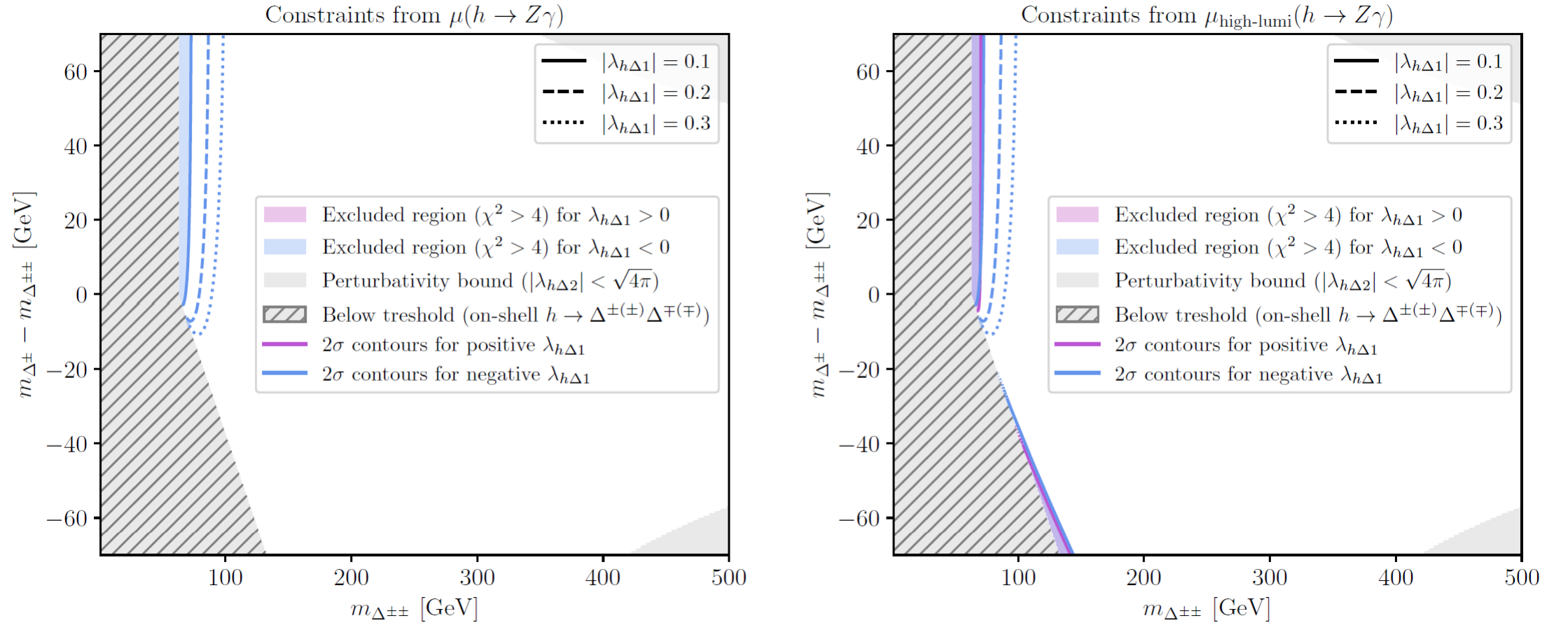


Figure 11: The contour plots obtained using the (a) current and (b) assumed improved measurement of $\mu(h \rightarrow Z\gamma)$.

**Probing Type-II Seesaw through associated Higgs production with a
photon in e^+e^- collisions**

Deriving the $e^+e^- \rightarrow h\gamma$ cross section (Feynman-'t Hooft gauge)

- tree-level amplitudes proportional to $y_e = m_e/v$
 - subleading in electron Yukawa
- dominant contributions at 1-loop:

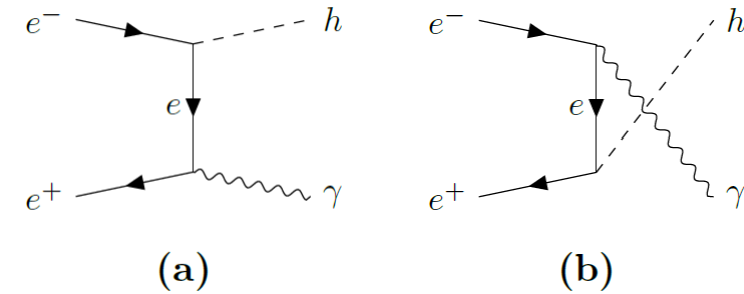


Figure 12: Tree-level diagrams for $e^+e^- \rightarrow h\gamma$.

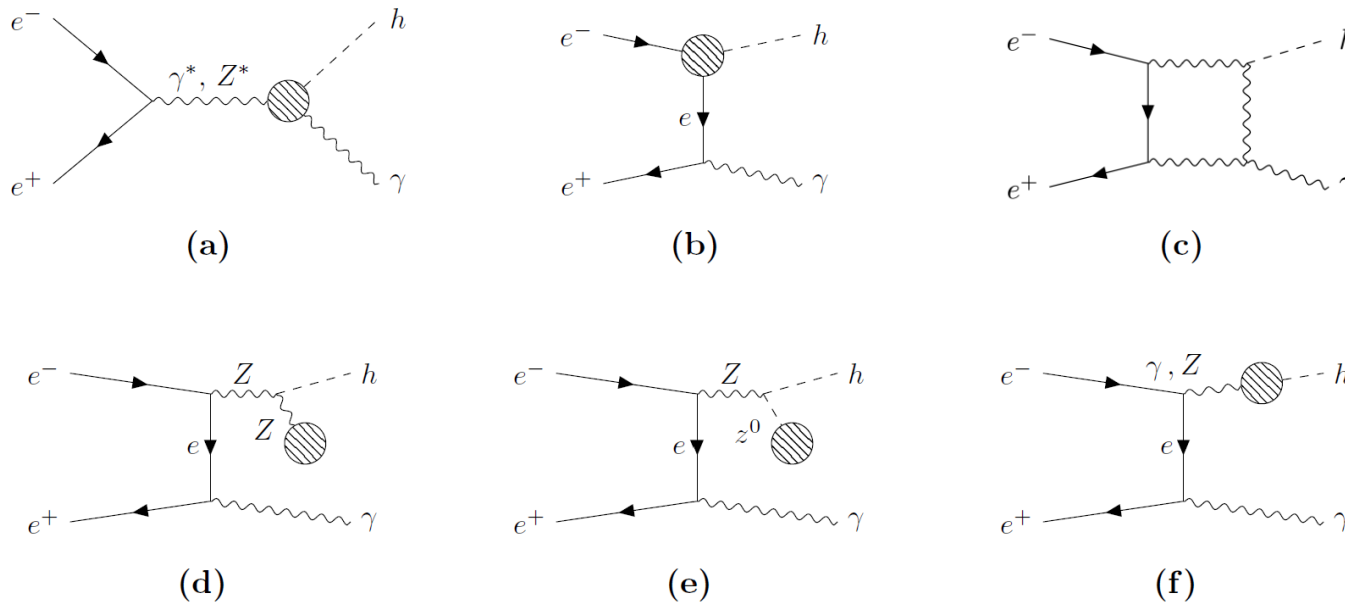


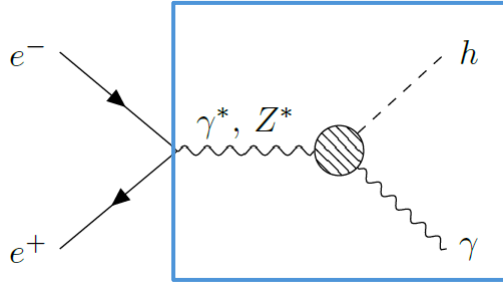
Figure 13: Some of 1-loop topologies contributing to $e^+e^- \rightarrow h\gamma$ in the SM.

- in the calculations, set $m_e \rightarrow 0$

Topologies contributing in this limit:

- tadpoles and 1-loop corr. to $\gamma(Z)$ - h mixing
 - these amplitudes vanish
- Z and W boxes
- Z and W penguins
- s-channel effective vertex diagrams

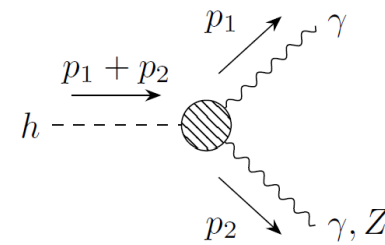
s-channel effective vertex diagrams



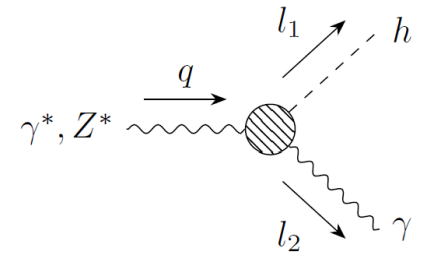
effective vertex function

can be obtained from
 $h \rightarrow \gamma\gamma(Z)$
 amplitudes

- γ^*, Z^* taken off-shell
 - changes in momentum direction
 - all amplitudes should be computed in the same gauge (Feynman-'t Hooft)
- Take $h \rightarrow Z\gamma$ amplitudes to find $h \rightarrow \gamma\gamma$ in Feynman-'t Hooft gauge



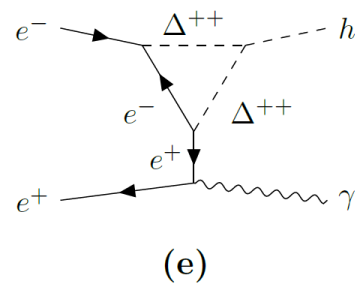
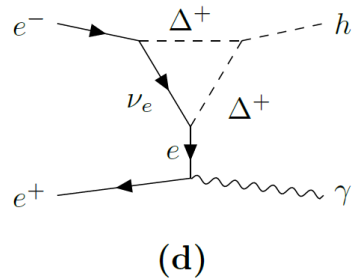
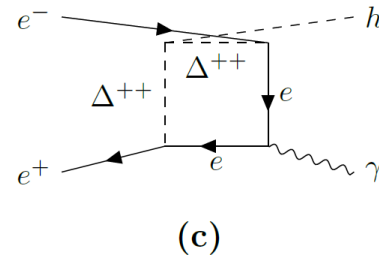
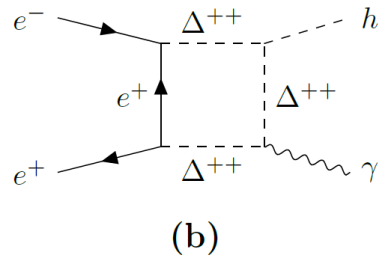
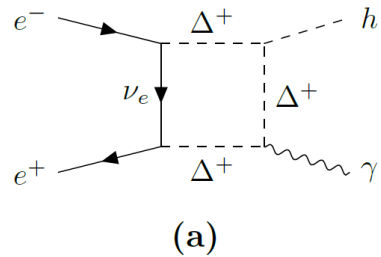
on-shell decay



effective vertex

Type-II corrections (in $v_\Delta \approx 0$ limit)

- charged scalar loops in effective vertices
- penguins and boxes with charged scalars in the loop



➤ proportional to triplet Yukawa:

$$\mathcal{M}_{\text{penguins, boxes}}^\Delta \propto \left(\frac{m_\nu}{v_\Delta} \right)^2$$

➤ These amplitudes could become large for

$$v_\Delta \ll m_\nu$$

➤ For present purposes considered

small-but-not-too-small- v_Δ limit: $m_\nu \ll v_\Delta \ll v$

➤ LO Type-II contributions to the scattering appear in s-channel eff. vertex diagrams

Deriving the $e^+e^- \rightarrow h\gamma$ cross section (Feynman-'t Hooft gauge)

Analytic results

- final amplitude expressed in a 6-dim. basis of Dirac bilinears:

V basis

$$\mathcal{M}(e^+e^- \rightarrow h\gamma) = \sum_{i=L,R} \mathcal{B}_1^i V_1^i + \mathcal{B}_2^i V_2^i + \mathcal{B}_3^i V_3^i$$

$\mathcal{B}_a^i$: coefficients of basis vectors

$$V_1^{L,R} = (k_1 \cdot \varepsilon^*) \bar{v}(k_2) \not{p}_2 P_{L,R} u(k_1),$$

$$V_2^{L,R} = (k_2 \cdot \varepsilon^*) \bar{v}(k_2) \not{p}_2 P_{L,R} u(k_1),$$

$$V_3^{L,R} = \bar{v}(k_2) \not{\varepsilon}^* P_{L,R} u(k_1)$$

- Ward identities satisfied after adding together the following groups of diagrams:

W boxes + W penguins + s -channel W loops, Z boxes + Z penguins, s -channel f loops.

- Total amplitude is gauge-invariant and is **forward-backward symmetric** (sym. under $u \leftrightarrow t$)

unpolarized differential cross section

$$\frac{d\sigma}{d\cos\theta} = \frac{s - m_h^2}{64\pi s} \frac{1}{4} \sum_{i=L,R} (u^2 |\mathcal{B}_1^i|^2 + t^2 |\mathcal{B}_2^i|^2)$$

total cross section (unpolarized)

$$\sigma = \int_{\min}^{\max} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

(avoiding collinear divergences)

$\min = -0.99, \max = +0.99$

Figure 14: SM prediction for the $e^+e^- \rightarrow h\gamma$ cross section as a function of $\sqrt{s}$. The dashed line indicates the branch cut at $\sqrt{s} = 2m_t$.

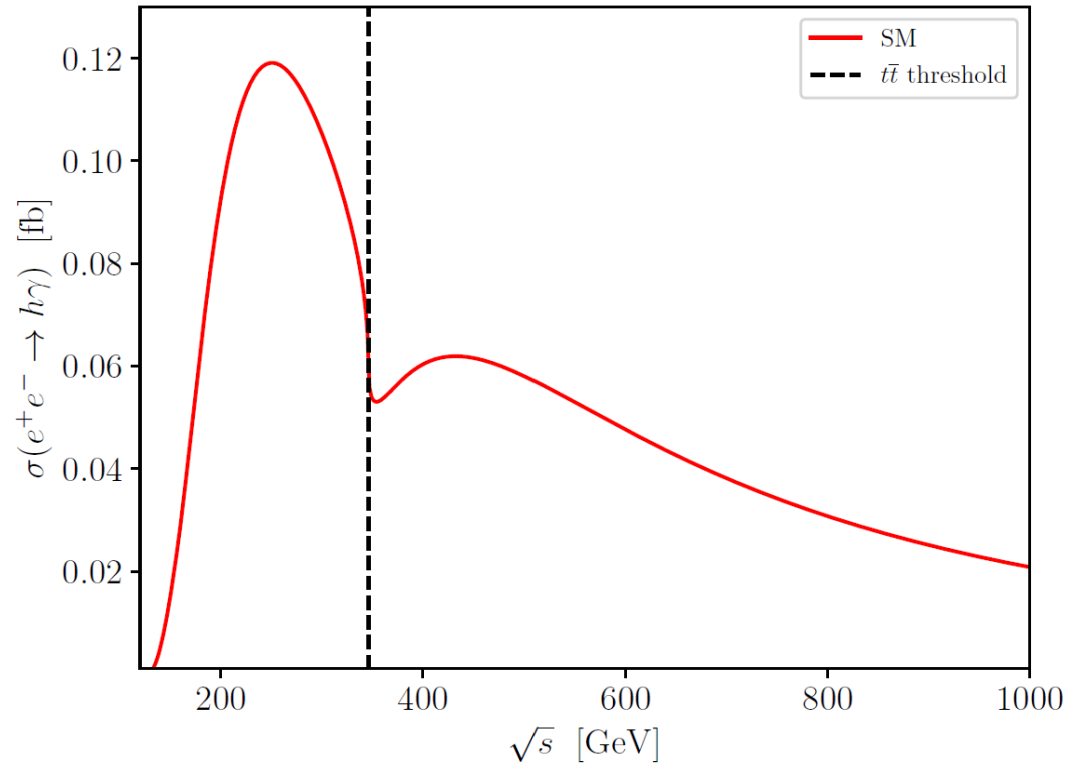
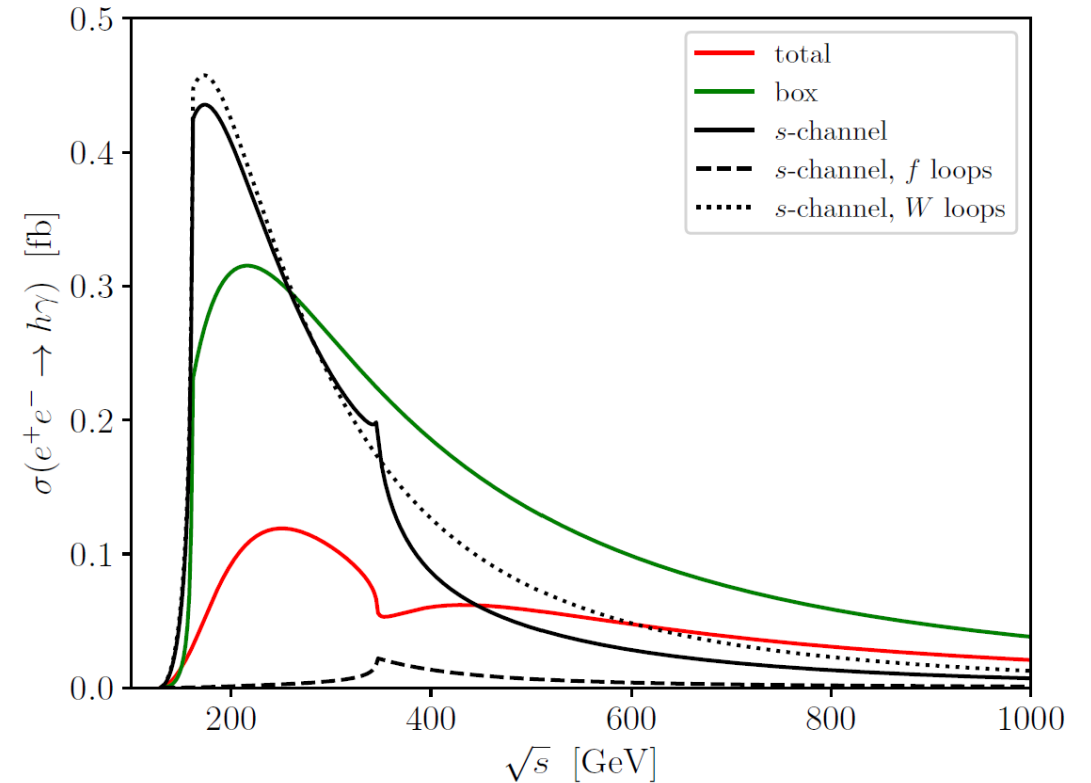


Figure 15: SM contributions to the $e^+e^- \rightarrow h\gamma$ cross section in Feynman-'t Hooft gauge.



- decomposition into contributions from different families of diagram topologies in SM:
 - amplitudes experience significant cancellations

Exploring the sensitivity of the cross section to Type-II effects

- for different points in the Type-II parameters space, computed:

$$R(\sigma) = \frac{\sigma_{\text{Type-II}}}{\sigma_{\text{SM}}} \quad \begin{array}{l} \text{ratio of Type-II and SM} \\ \text{unpolarized cross sections} \end{array}$$

- at 3 center-of-mass energies attainable by some of the future collider projects:

$$\sqrt{s} = 360 \text{ GeV (FCC-ee, CEPC)}, \quad \sqrt{s} = 550 \text{ GeV (LCF)}, \quad \sqrt{s} = 1000 \text{ GeV (CLIC)}$$

[Benedikt et al., 2025]

[Abramowicz et al., 2025]

[CERN, 2018]

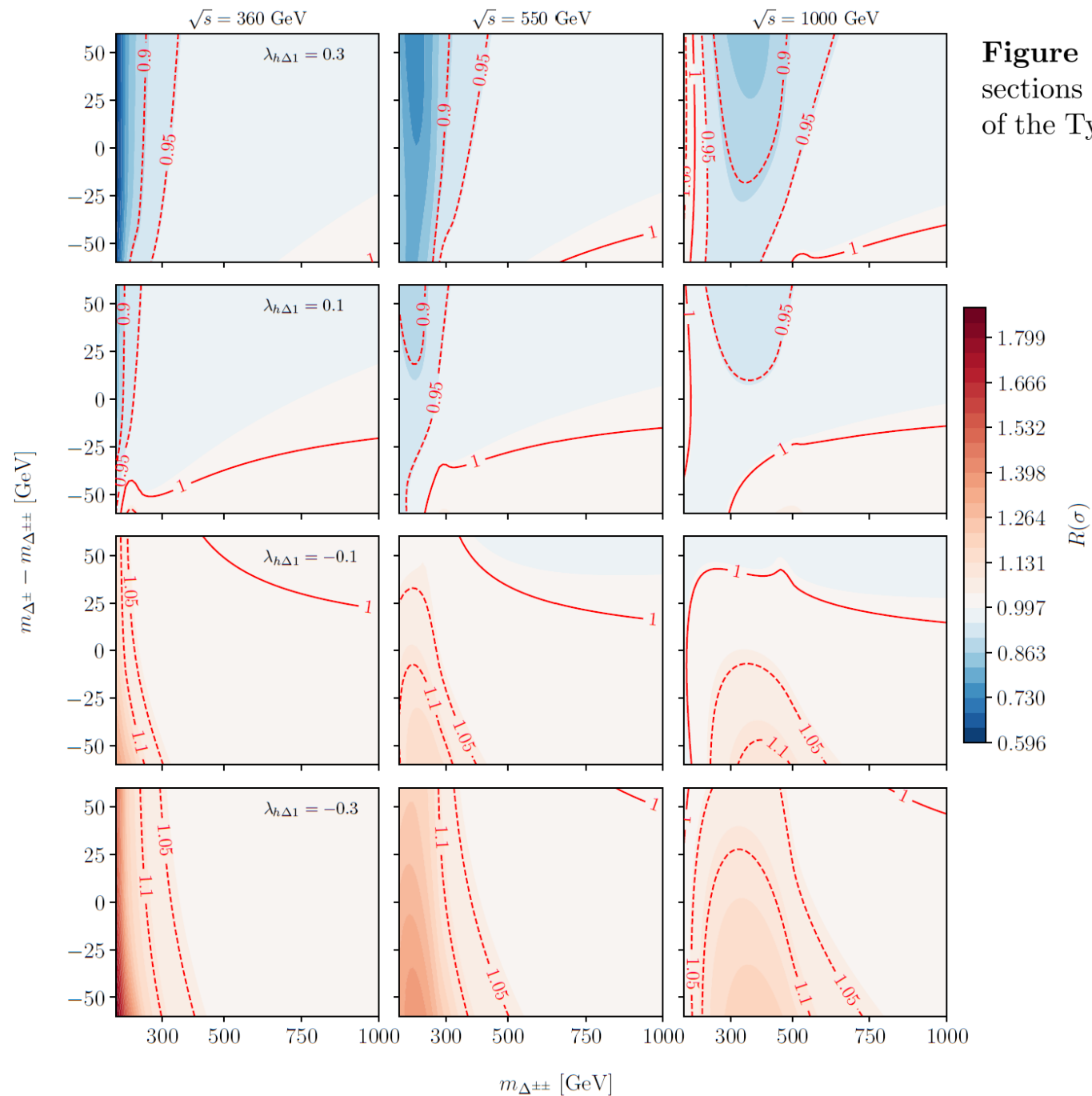


Figure 16: Contour plots of the ratio of the predicted Type-II and SM cross sections at three different $\sqrt{s}$ and evaluated across different combinations of the Type-II parameters. The SM prediction is indicated by the solid red line.

- σ experiences noticeable departures from SM prediction
- assume 10% deviations might be detectable:
 - inspect regions unconstrained by Higgs diphoton decay where:

$$R(\sigma) \leq 0.9 \text{ or } R(\sigma) \geq 1.1$$

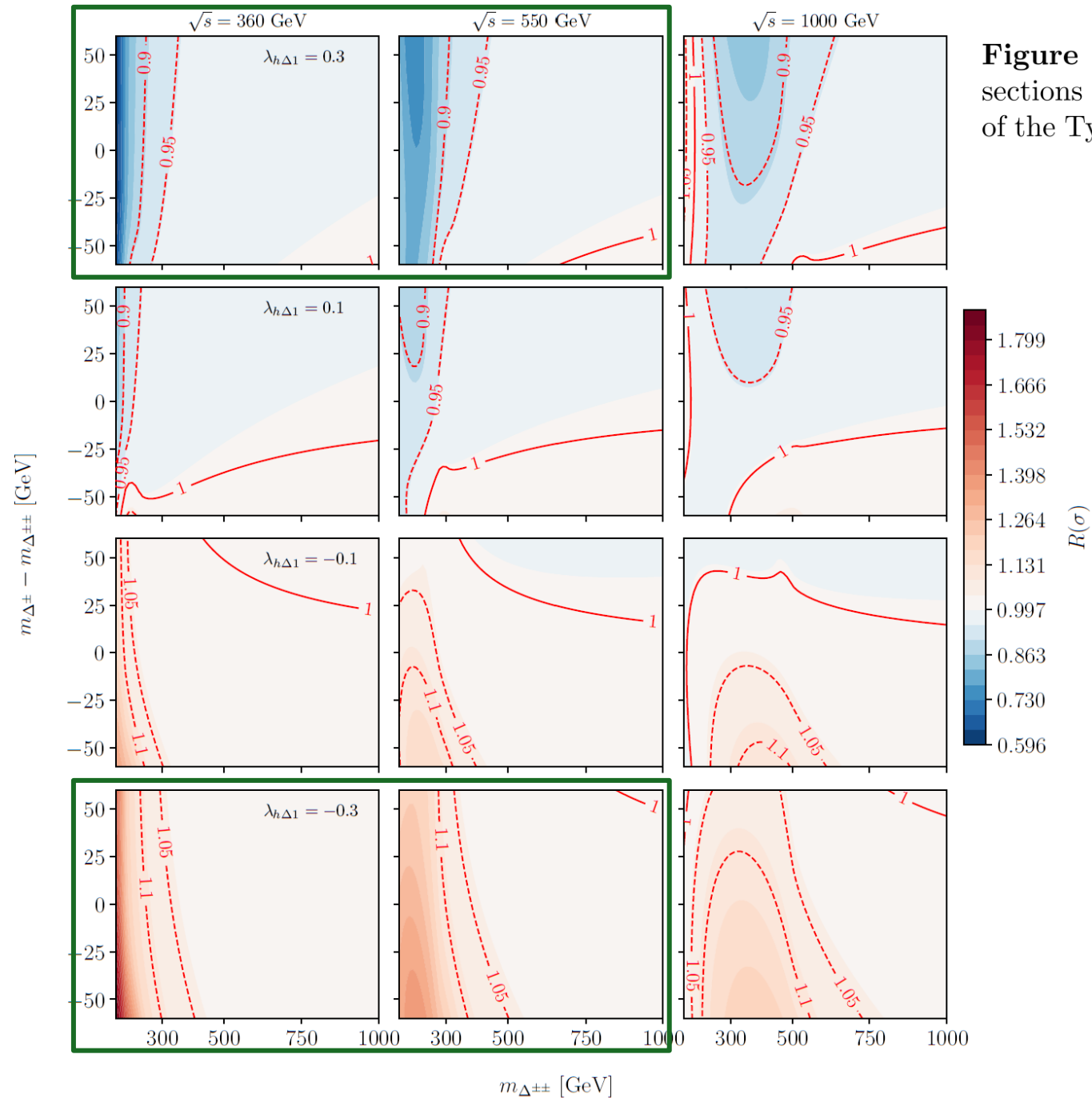
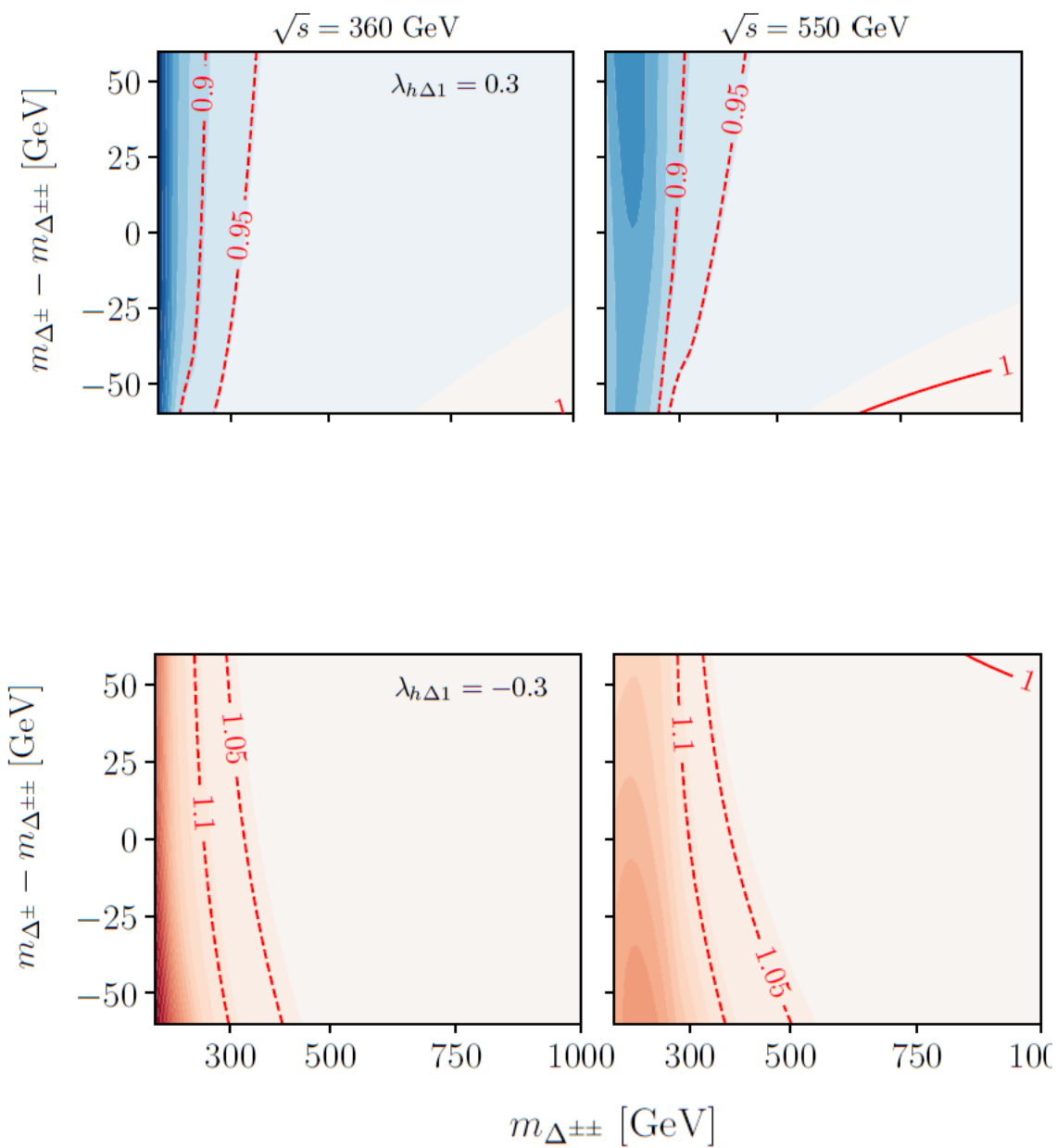


Figure 16: Contour plots of the ratio of the predicted Type-II and SM cross sections at three different $\sqrt{s}$ and evaluated across different combinations of the Type-II parameters. The SM prediction is indicated by the solid red line.

- σ experiences noticeable departures from SM prediction
- assume 10% deviations might be detectable:
 - inspect regions unconstrained by Higgs diphoton decay where:

$$R(\sigma) \leq 0.9 \text{ or } R(\sigma) \geq 1.1$$



positive bi-quadratic couplings

$e^+e^- \rightarrow h\gamma$ more sensitive to Type-II contributions than $h \rightarrow \gamma\gamma$ for negative mass splittings

negative bi-quadratic couplings

$e^+e^- \rightarrow h\gamma$ could be particularly effective in probing $\lambda_{h\Delta 1} < 0$ scenarios

(largely unconstrained by $h \rightarrow \gamma\gamma$)

CONCLUSIONS

- derived analytic formulae for $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$ decay widths in SM and Type-II for $v_\Delta \ll v$
 - found regions excluded at 2σ by $h \rightarrow \gamma\gamma$; $h \rightarrow Z\gamma$ offers no additional constraints
- provided analytic results for associated Higgs production with a photon in electron-positron collisions in the Type-II Seesaw
 - employed $m_\nu \ll v_\Delta \ll v$ limit
 - once measured, the process might provide access to regions which are comparatively weakly constrained by the diphoton decay

Future analysis outlook:

- direct searches of diphoton decay of the other neutral scalar in Type-II (Δ^0)
- polarized scattering cross section
- very-small- v_Δ (large Type-II Yukawas) regime: additional Type-II diagrams

BACKUP SLIDES

Brief discussion of constraints on Type-II parameters

Theoretical consistency considerations:

- Vacuum stability
- Tree-level unitarity
- Perturbativity

Constraints from EWPT (S, T oblique parameters, ρ parameter)

Constraints from direct searches:

- LFV processes
- Cascade decays
- Leptonic (very-small v_Δ) and bosonic decays (small-but-not-too-small v_Δ), LNV window

Predicted signal strength

➤ decoupling of scalar loops for large masses of the doubly charged (Appelquist-Carazzone decoupling theorem)

[Appelquist and Carazzone, 1975]

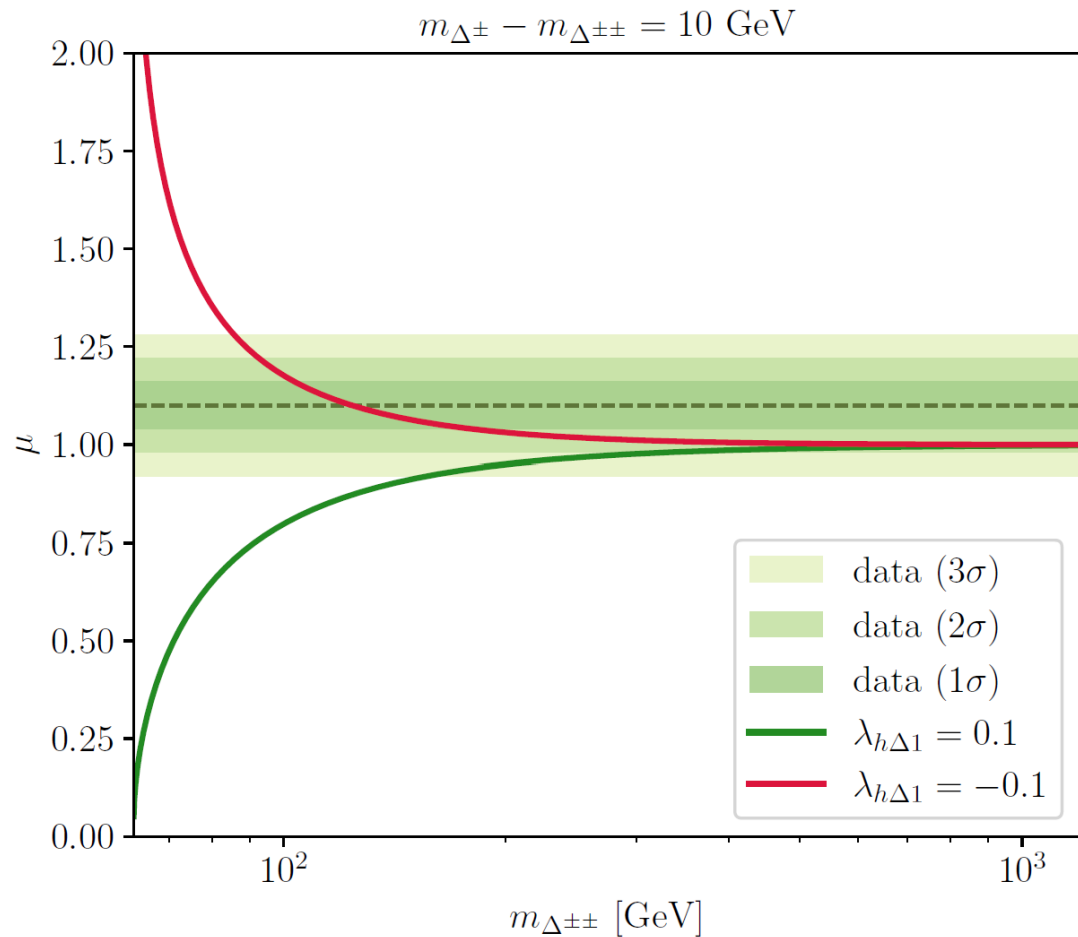


Figure 8: Predicted $h \rightarrow \gamma\gamma$ signal strength in Type-II.

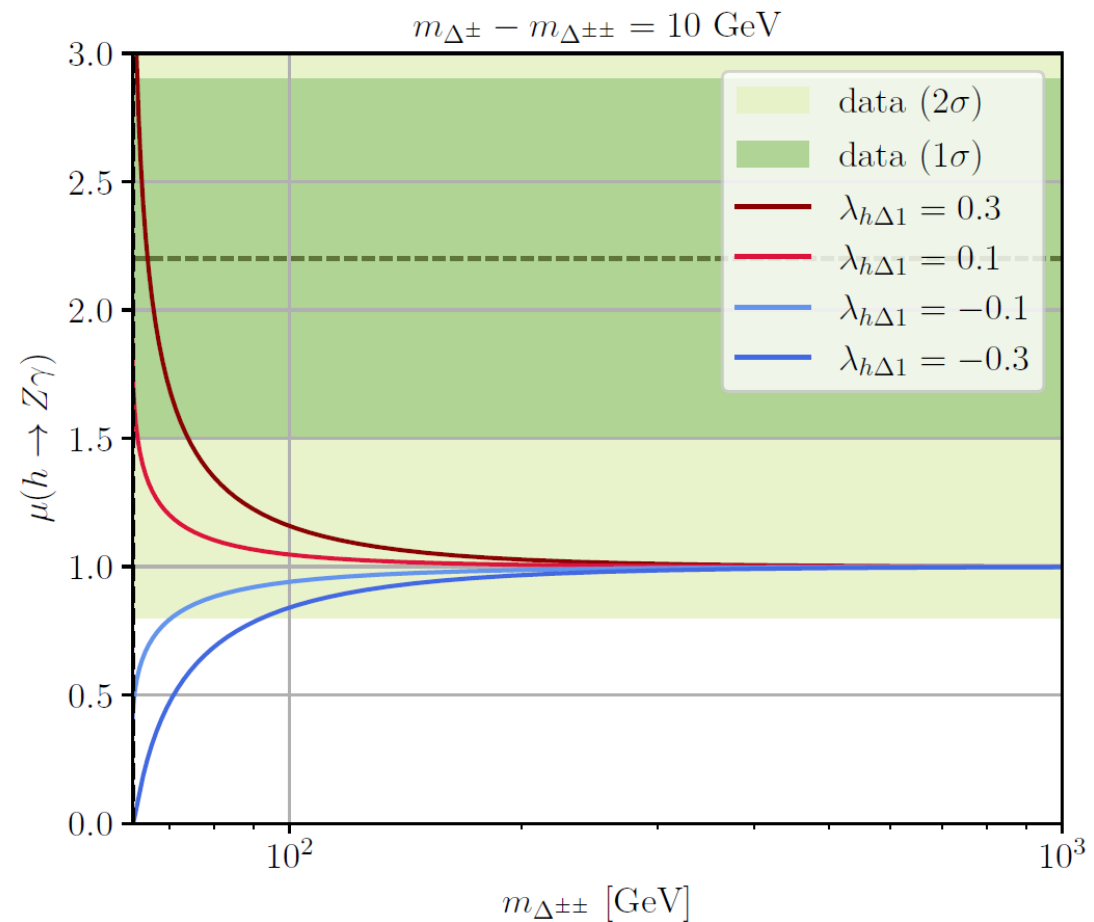
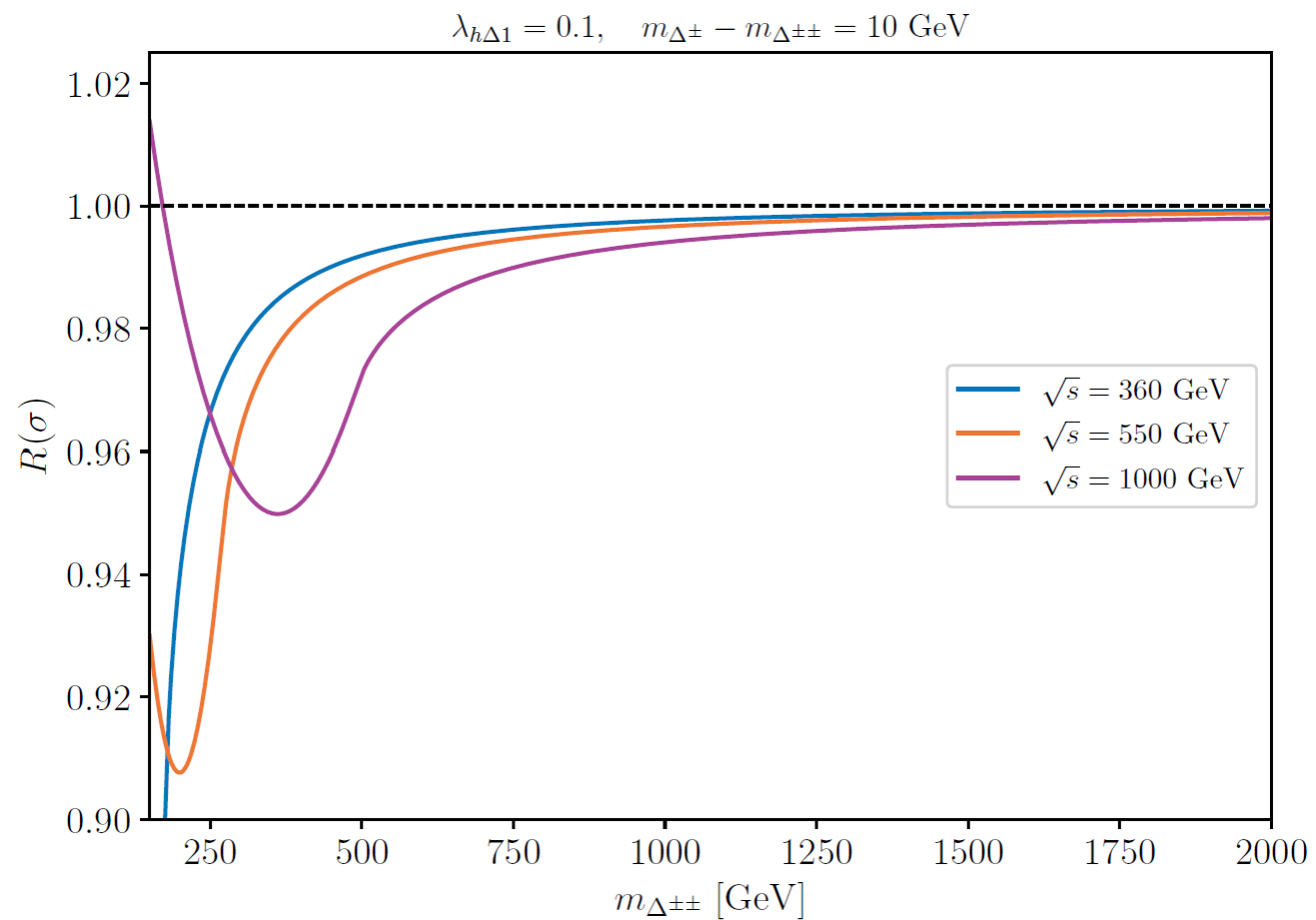
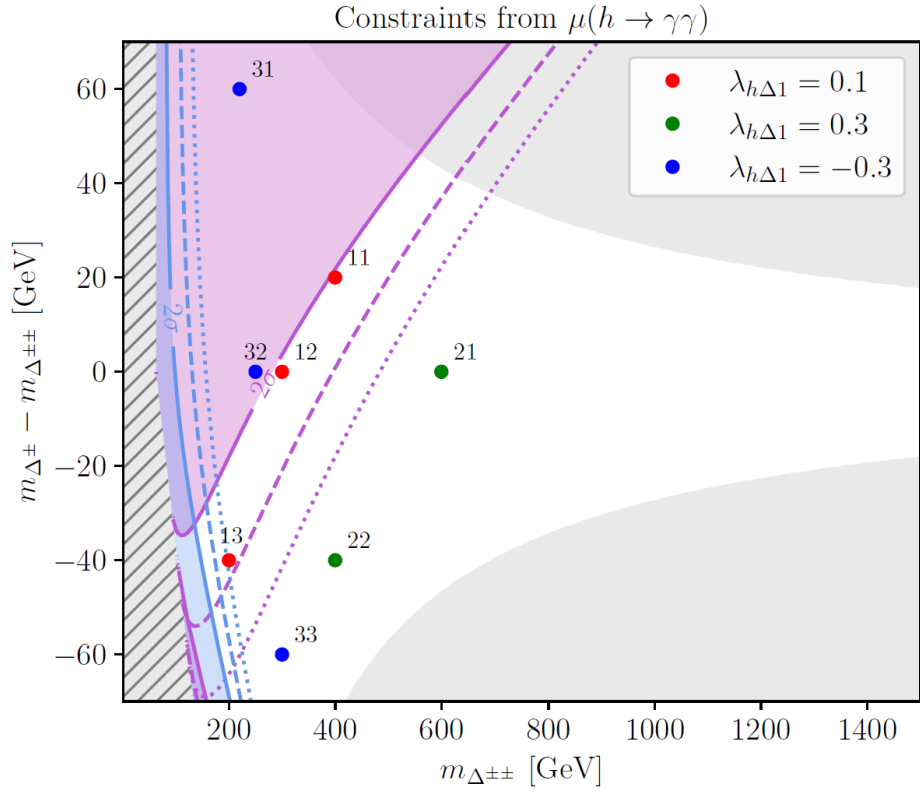


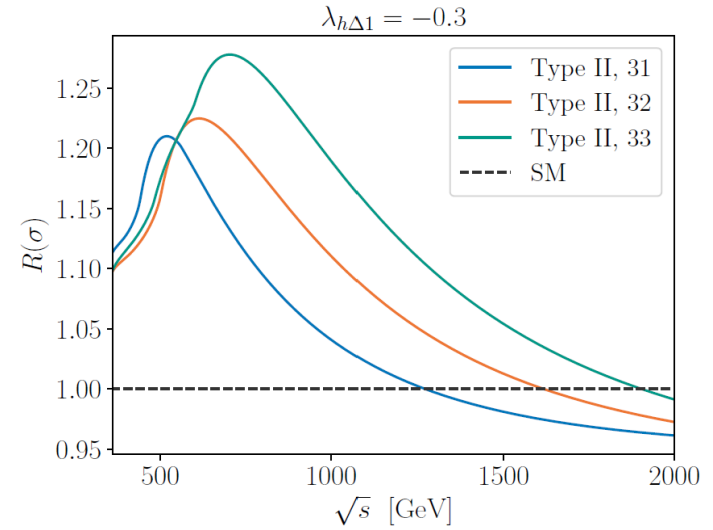
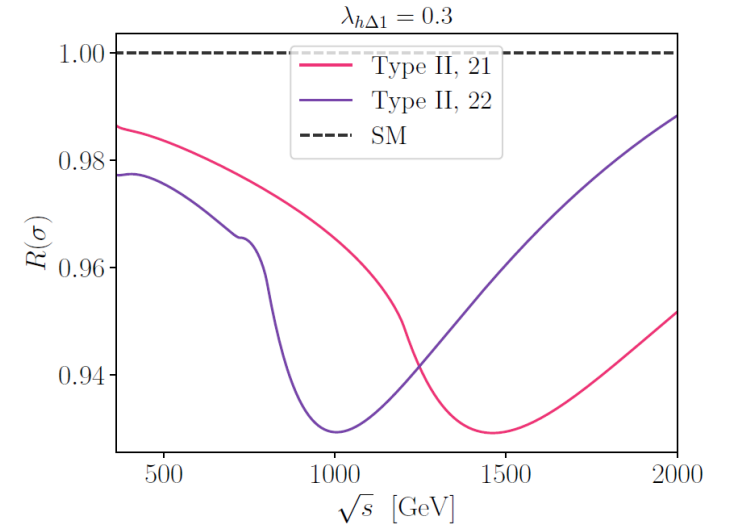
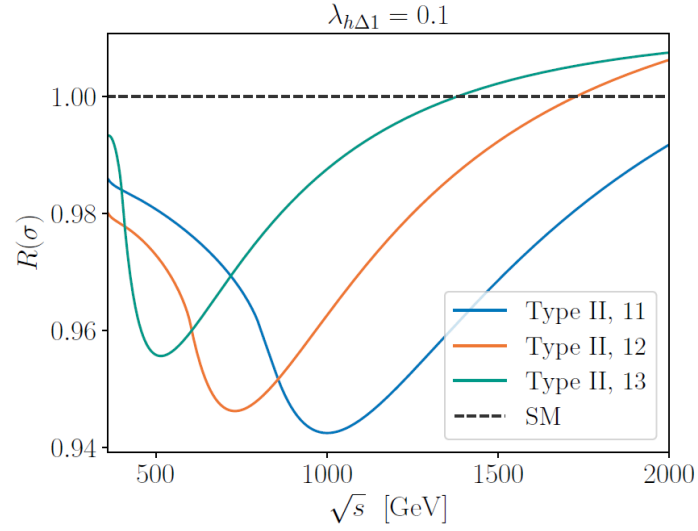
Figure 9: Predicted $h \rightarrow Z\gamma$ signal strength in Type-II.

Decoupling of charged scalar loops in associated Higgs production



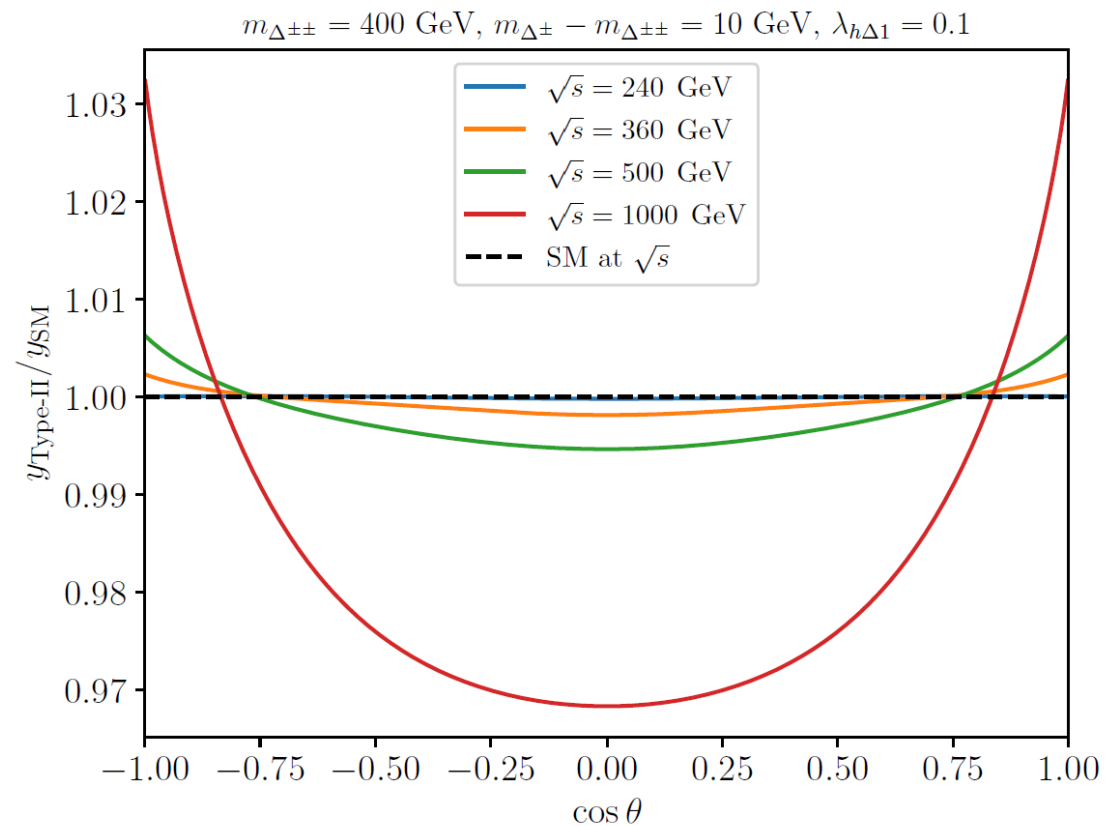
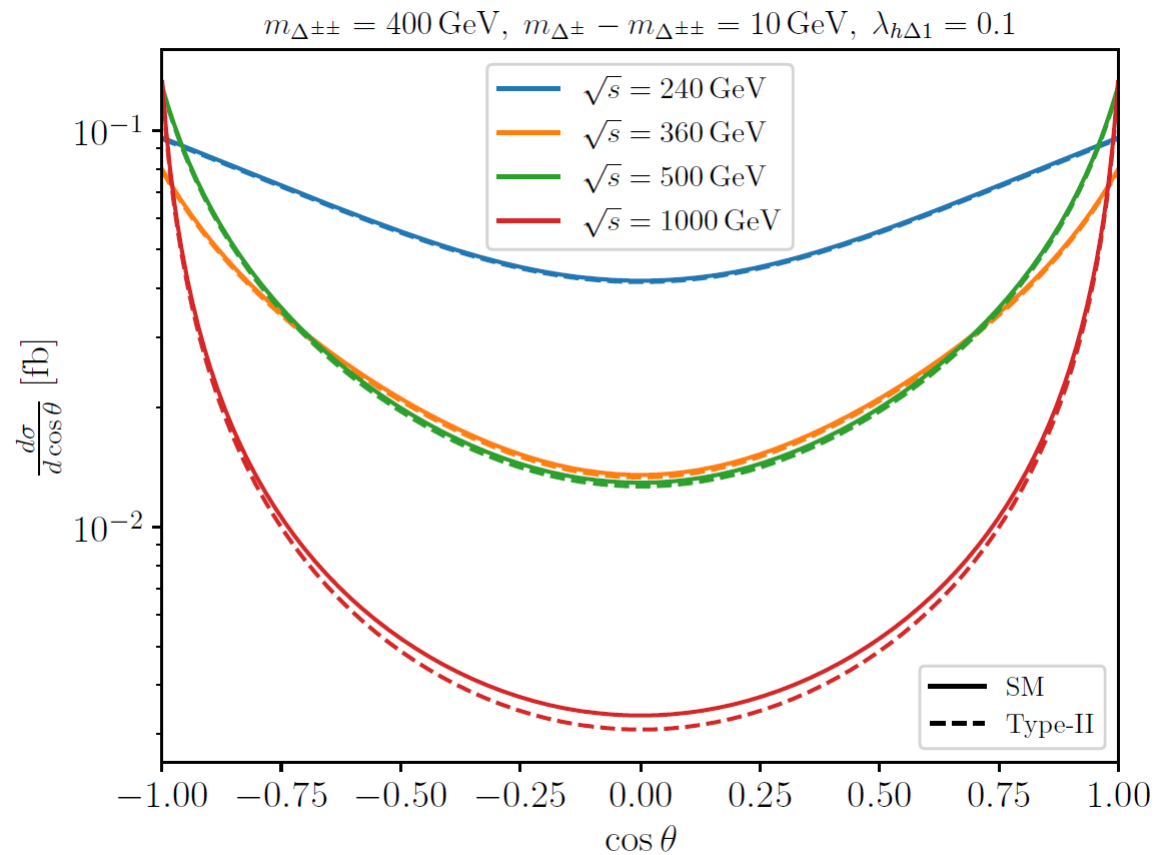


Configuration	$\lambda_{h\Delta 1}$	$m_{\Delta^{++}}$ [GeV]	$m_{\Delta^\pm} - m_{\Delta^{++}}$ [GeV]
11	0.1	400	20
12		300	0
13		200	-40
21	0.3	600	0
22		400	-40
31	-0.3	220	60
32		250	0
33		300	-60



normalized differential cross section (unpolarized)

$$y = \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta}$$



Computing $h \rightarrow \gamma\gamma$ decay width (unitary gauge)

total SM amplitude

[Ward, 1950]

$$\mathcal{M}_{\text{SM}} = \mathcal{M}_W + \sum_f \mathcal{M}_f = \frac{e^2 g}{(4\pi)^2 m_W} F_{\text{SM}} (p_1 \cdot p_2 g^{\mu\nu} - p_1^\nu p_2^\mu) \varepsilon_\mu(p_1) \varepsilon_\nu(p_2)$$

Ward identities:

$$p_1^\mu \mathcal{M}_\mu = p_2^\nu \mathcal{M}_\nu = 0$$

dimensionless factor: $F_{\text{SM}} = F_W + \sum_f N_f Q_f^2 F_f$,

N_f : color factor

Q_f : charge

$$\begin{aligned} \bullet \quad F_W &= 2 + 3\beta_W + 3(2\beta_W - \beta_W^2) f(\beta_W), & f(\beta) &= \begin{cases} \arcsin^2(\beta^{-1/2}), & \beta \geq 1 \\ -\frac{1}{4} \left(\ln \frac{1+\sqrt{1-\beta}}{1-\sqrt{1-\beta}} - i\pi \right)^2, & \beta < 1. \end{cases} \\ \bullet \quad F_f &= -2\beta_f (1 + (1 - \beta_f) f(\beta_f)) & \beta_i &= \frac{4m_i^2}{m_h^2} \end{aligned}$$

charged scalar loop amplitude (arbitrary scalar Δ)

$$\mathcal{M}_\Delta = \frac{C_{h\Delta\Delta} v Q_\Delta^2 e^2}{(4\pi)^2 m_\Delta^2} F_\Delta (p_1 \cdot p_2 g^{\mu\nu} - p_1^\nu p_2^\mu) \varepsilon_\mu(k_1) \varepsilon_\nu(p_2)$$

dimensionless factor: $F_\Delta = \beta_\Delta (1 - \beta_\Delta f(\beta_\Delta))$

- total amplitude UV-finite
- satisfies Ward identities

Decay of the triplet-like neutral scalar

$$\Gamma_{\Delta^0 \rightarrow \gamma\gamma} = \frac{m_{\Delta^0}^3 G_F}{8\sqrt{2}\pi} \left(\frac{\alpha}{4\pi} \right)^2 |F_{\text{Type-II}}(\Delta^0)|^2$$

$$\text{finite-}v_\Delta \text{ effect: } \Gamma \propto v_\Delta^2$$

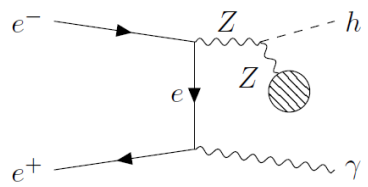
$$F_{\text{Type-II}}(\Delta^0) = F_{\text{SM}}|_\Delta(\Delta^0) + \sum_{\Delta} \frac{C_{\Delta^0\Delta\Delta} v Q_\Delta^2 m_W}{m_\Delta^2 g} F_\Delta, \quad \Delta = \{\Delta^\pm, \Delta^{\pm\pm}\}$$

$$F_{\text{SM}}|_\Delta(\Delta^0) = \frac{g}{2m_W} (s_\xi v - 2c_\xi v_\Delta) F_W - 2 \frac{s_\xi m_W}{g v} \sum_f N_f Q_f^2 F_f$$

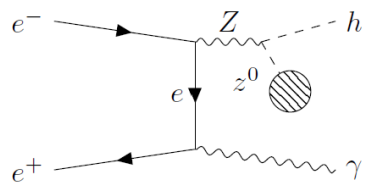
$$m_{\Delta^\pm} - m_{\Delta^{\pm\pm}} = 10 \text{ GeV}, \quad m_{\Delta^{\pm\pm}} = 1000 \text{ GeV}, \quad \lambda_{h\Delta 1} = \lambda_{\Delta 1} = \lambda_{\Delta 2} = 1, \quad v_\Delta = 0.1 \text{ GeV} :$$

$$\Gamma_{\Delta^0 \rightarrow \gamma\gamma} \simeq 1.3 \cdot 10^{-10} \text{ GeV}$$

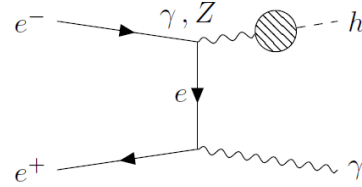
$$v_\Delta = 42 \text{ keV} : \quad \Gamma_{\Delta^0 \rightarrow \gamma\gamma} \simeq 2.4 \cdot 10^{-17} \text{ GeV}$$



(d)



(e)



(f)

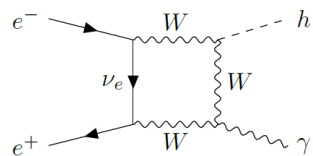
- 1-loop corrections to Z boson and neutral would-be Goldstone vev **(d), (e)**

➤ these amplitudes vanish

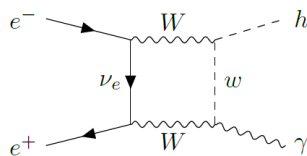
- 1-loop correction to $\gamma(Z)$ -h mixing **(f)**

➤ also vanish

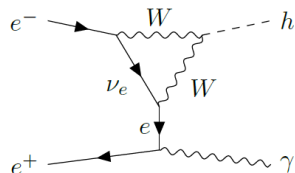
Penguins and boxes:



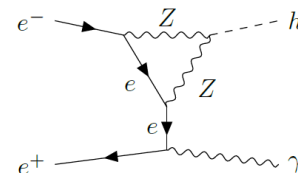
(Box 1)



(Box 2)



(p1)



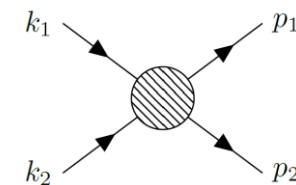
(p2)

➤ in the calculations, set $m_e \rightarrow 0$

On-shell conditions:

$$k_1^2 = k_2^2 = m_e^2 \approx 0,$$

$$p_1^2 = m_h^2, \quad p_2^2 = 0$$

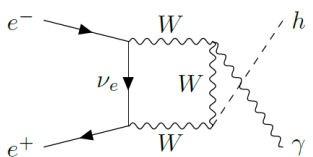


Mandelstam variables:

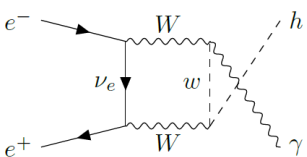
$$s = (k_1 + k_2)^2 = (p_1 + p_2)^2,$$

$$t = (k_1 - p_1)^2 = (p_2 - k_2)^2,$$

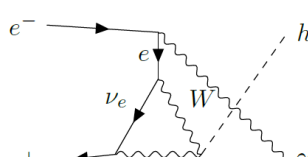
$$u = (k_1 - p_2)^2 = (p_1 - k_2)^2.$$



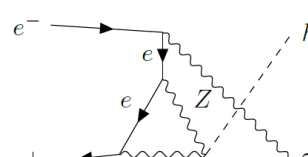
(Box 1')



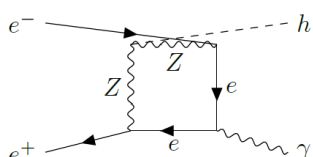
(Box 2')



(p1')



(p2')



(Box 3)

- amplitudes symmetric under $u \leftrightarrow t$
- not gauge-invariant on their own

Forward-backward asymmetry

$$\mathcal{A}_{\text{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \quad \sigma_F \equiv \int_0^{\max} \frac{d\sigma}{d\cos\theta} d\cos\theta, \quad \sigma_B \equiv \int_{\min}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta,$$

$$t = -\frac{1}{2} (s - m_h^2) (1 - \cos\theta)$$

$$u = -\frac{1}{2} (s - m_h^2) (1 + \cos\theta)$$

From gauge invariance:

$$\mathcal{B}_3^i = \frac{1}{2} (u\mathcal{B}_1^i + t\mathcal{B}_2^i) \quad |\overline{\mathcal{M}}|^2 = \frac{s}{8} \sum_{i=L,R} (u^2 |\mathcal{B}_1^i|^2 + t^2 |\mathcal{B}_2^i|^2)$$

Table 6.1: SM contributions to the $e^+e^- \rightarrow h\gamma$ amplitude in Feynman-'t Hooft gauge.

Family of diagrams	prefactor	$\mathcal{B}_1^L$	$\mathcal{B}_1^R$	$\mathcal{B}_2^L$	$\mathcal{B}_2^R$	$\mathcal{B}_3^L$	$\mathcal{B}_3^R$	sec.
tadpoles + WF corr's	n/a	0	0	0	0	0	0	6.1.2
W penguins	$\frac{eg^3m_W}{16\pi^2}$	0	0	0	0	$\mathcal{B}_3(\text{W pen})$	0	6.1.3
Z penguins	$\frac{eg^3m_W}{32\pi^2} \frac{m_Z}{c_W^3}$	0	0	0	0	$z_L^2 \mathcal{B}_3(\text{Z pen})$	$z_R^2 \mathcal{B}_3(\text{Z pen})$	6.1.3
W boxes	$\frac{eg^3m_W}{16\pi^2}$	$\mathcal{B}_1(\text{W box})$	0	$\mathcal{B}_2(\text{W box})$	0	$\mathcal{B}_3(\text{W box})$	0	6.1.4
Z box	$\frac{eg^3m_Z}{16\pi^2 c_W^3}$	$z_L^2 \mathcal{B}_1(\text{Z box})$	$z_R^2 \mathcal{B}_1(\text{Z box})$	$z_L^2 \mathcal{B}_2(\text{Z box})$	$z_R^2 \mathcal{B}_2(\text{Z box})$	$z_L^2 \mathcal{B}_3(\text{Z box})$	$z_R^2 \mathcal{B}_3(\text{Z box})$	6.1.4
γ^* s-channel	$\frac{e}{s}$	K_3^γ		K_3^γ		K_1^γ		6.1.5
Z^* s-channel	$-\frac{g}{2c_W(s-m_Z^2)}$	$z_L K_3^Z$	$z_R K_3^Z$	$z_L K_3^Z$	$z_R K_3^Z$	$z_L K_1^Z$	$z_R K_1^Z$	6.1.5

Table 6.2: Type-II contributions to the $e^+e^- \rightarrow h\gamma$ amplitude in Feynman-'t Hooft gauge.

Family of diagrams	prefactor	$\mathcal{B}_1^L$	$\mathcal{B}_1^R$	$\mathcal{B}_2^L$	$\mathcal{B}_2^R$	$\mathcal{B}_3^L$	$\mathcal{B}_3^R$	sec.
γ^* s-channel (Type-II)	$\frac{e}{s} A_\Delta^{\gamma*}$	$K_{3,\Delta}^\gamma$		$K_{3,\Delta}^\gamma$		$K_{1,\Delta}^\gamma$		6.2
Z^* s-channel (Type-II)	$-\frac{g}{2c_W(s-m_Z^2)} A_\Delta^{Z*}$	$z_L K_{3,\Delta}^Z$	$z_R K_{3,\Delta}^Z$	$z_L K_{3,\Delta}^Z$	$z_R K_{3,\Delta}^Z$	$z_L K_{1,\Delta}^Z$	$z_R K_{1,\Delta}^Z$	6.2

THE STANDARD MODEL AS A SPONTANEOUSLY BROKEN GAUGE THEORY

Electroweak symmetry breaking

$$\boxed{\text{SU}(2)_L \otimes \text{U}(1)_Y \rightarrow \text{U}(1)_Q}$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad Y_\phi = 1/2 \quad \text{Higgs doublet} \quad Q : \text{electromagnetic charge}$$

$$\boxed{Q = T^3 + Y}$$

Electromagnetic charge unbroken

➤ only the neutral component can have nonzero vev

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v^2 = \mu^2 / \lambda$$

Expanding around the vev:

would-be Goldstones
(absorbed by the W, Z
bosons)

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}w^+ \\ v + h + iz \end{pmatrix}$$

the Higgs field

—————→
from kinetic terms
for the Higgs doublet

$$\mathcal{D}_\mu \phi = (\partial_\mu + igT^a W_\mu^a + ig'Y_\phi B_\mu) \phi$$

covariant derivative of the Higgs doublet

Masses of the electroweak bosons:

- $m_{W, \text{SM}}^2 = \frac{1}{4}g^2v^2,$
- $m_{Z, \text{SM}}^2 = \frac{1}{4}(g^2 + g'^2)v^2,$
- $m_{A, \text{SM}}^2 = 0.$

weak mixing angle $\tan \theta_W = \frac{g'}{g}$

THE STANDARD MODEL AS A SPONTANEOUSLY BROKEN GAUGE THEORY

Lepton masses in the Standard model

- Gauge-invariant terms:

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R$$

Yukawa coupling

$$\mathcal{L}_{\text{Yukawa}}^{\text{leptons}} = -y \bar{L} \phi e_R + \text{h.c.}$$

no right-handed neutrino

↓ SSB

$$\begin{aligned} -y \bar{L} \langle \phi \rangle e_R + \text{h.c.} &= y \begin{pmatrix} \bar{\nu}_L & \bar{e}_L \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} e_R \\ &= -y v \bar{e}_L e_R + \text{h.c.} = -m_e \bar{e} e \end{aligned}$$

- Dirac-type mass term for electron
- **Neutrinos remain massless after SSB.**